FHR 2701-4

EVALUATION OF HYDRAULIC FLUIDS FOR USE IN ADVANCED SUPERSONIC AIRCRAFT

by

F. Damasco

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 3-7263

FAIRCHILD HILLER
Republic Aviation Division
Farmingdale, Long Island, New York

Kg 46168

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FOURTH SEMIANNUAL REPORT

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FOR USE IN ADVANCED SUPERSONIC AIRCRAFT

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ABSTRACT

Chlorinated silicone (F-50), modified polyphenyl ether (MCS-293), deep-dewaxed super-refined mineral oil (MLO 60-294), halogenated polyaryl (MCS-3104), and fluorocarbon (PR-143AB) fluids are under evaluation for possible use in hydraulic systems in advance supersonic aircraft. The above fluids were screen tested in a simple pump loop at 400°, 500° and 600°F pump inlet temperature and at 3000 psi for periods up to 50 hours at each temperature. Based on their performance in the pump tests the mineral oil and the fluorocarbon fluid were recommended for endurance testing in a complete hydraulic system at 450° and 500°F pump inlet temperatures, respectively, with hot spots to a maximum of 600°F.

EVALUATION OF HYDRAULIC FLUIDS FOR USE IN ADVANCED SUPERSONIC AIRCRAFT

by F. Damasco

Fairchild Hiller
Republic Aviation Division

SUMMARY

In this program the capabilities of five selected fluids are being investigated for potential use in advanced supersonic aircraft hydraulic systems. The scope of this program is the determination of: pertinent physical properties, lubricating ability of the fluids with selected bearing materials, pumpability of the fluids at elevated temperatures and pressures, and endurance test limits on two of the best fluids screened.

This report describes work accomplished during the fourth six-month period of NASA Contract NAS 3-7263, ending 24 March 1967. Activities during the reporting period included:

- Screening of the last three candidate fluids in a simple pump loop for 50 hours at each temperature of 400°, 500° and 600°F and at 3000 psi.
- Revision of the two pump loops for the endurance test to accommodate an actuator, spool valve, hot spot simulator, and filters of different pore sizes.
- Start of the endurance testing of MLO 60-294 mineral oil and PR-143AB fluorocarbon.

INTRODUCTION

Future advanced supersonic aircraft will present difficult technological problems associated with high operating temperatures. Further complication arises from stringent requirements for long-term integrity and economical operation.

Reliable operation of flight controls and utilities is one of the major problem areas. Selection of a power transfer medium largely determines the subsequent design and performance characteristics of the system. The fundamental goal of this program is the selection of hydraulic fluids suitable for 3000 hours of reliable operation in a temperature range of -40° to +600°F.

Several experimental hydraulic fluids that approach the design requirements are currently available while several others are presently being developed. Experience has shown that the most realistic evaluation of a fluid's potential is accomplished through simulated system testing with optimized aircraft-type pumps.

This program is divided into four tasks:

Task I - Selection and physical property determination of five fluids

Task II - Determination of optimum pump bearing materials by boundary lubrication tests

Task III - Screening of candidate fluids in a simple pump loop

Task IV - Endurance testing in a simulated system of the best two fluids as determined in Task III.

TASK III - SIMPLE PUMP LOOP TESTS

Tasks I, II and a portion of III were completed and previously reported. All work performed under Task III is summarized in this report. Of the five candidate fluids, F-50 silicone oil and MCS-3104 halogenated polyaryl fluid failed during the 500°F pump test. MCS-293 modified polyphenyl ether failed during the pump break-in test. MLO 60-294 deep-dewaxed superrefined mineral oil and PR-143AB* fluorocarbon fluid successfully completed the 600°F pump tests and are scheduled for the 3000-hour endurance test in a complete hydraulic system in Task IV. The pump, test system, and property changes on the five fluids during the pump loop tests in Task III are described below.

The pump used, a product of Pesco Products Division of Borg-Warner, is a prototype of the one developed for use with a chlorinated silicone oil at a rated 400°F maximum pump inlet temperature on the General Electric J-93 engine, Ref. 1. The pump was designed for a temperature limit of 400°F which is below the temperature requirements of this program.

Exploded and cross-sectional views of the pump are illustrated in Figures 1 and 2, respectively. The pump was designed for variable flow with a maximum displacement of 0.77 cubic inch per revolution at 3000 psi. It has a fixed stroke nine-piston unit driven by a rotating fixed angle swash plate at 3600 rpm. The pistons have hemispherical shoes which are not swaged to the piston sockets. The shoes bear against the swash plate. Bearing on the opposite face of the swash plate are eleven main thrust bearings. The bearings are mounted in sockets to permit self adjustment to the operating speed, load and fluid viscosity. A specified end clearance of 9 to 11 mils is also necessary to allow the shoes and thrust bearings to align themselves.

Variable fluid displacement is achieved by holding the inlet valve open for the first part of the pressure stroke of the piston. A nine-pronged control plate

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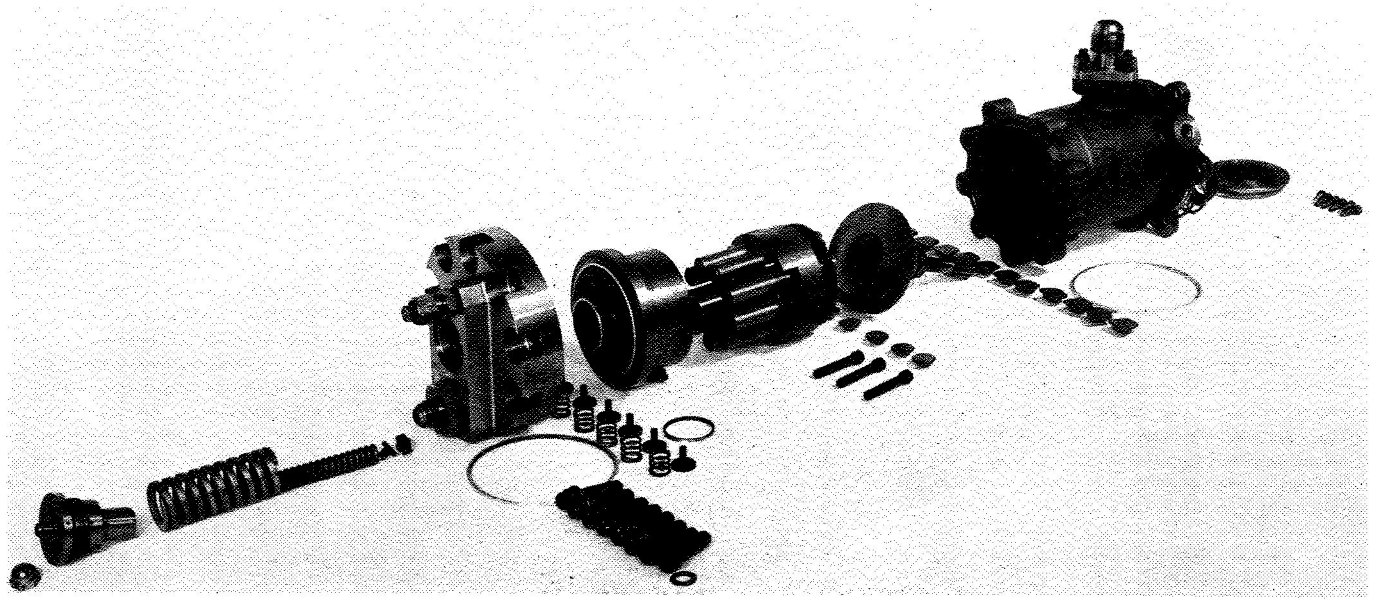
* This fluid is currently designated as Krytox 143AB



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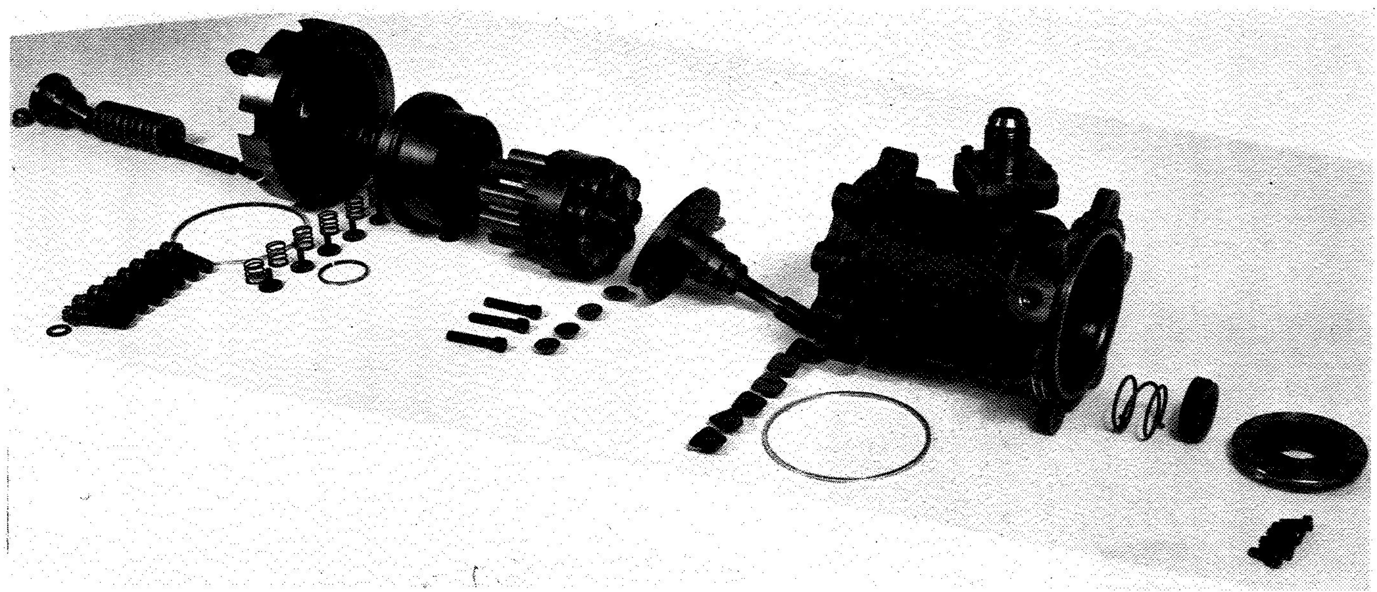

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Figure 1. Exploded Views of Pesco Pump Model X 013304-010

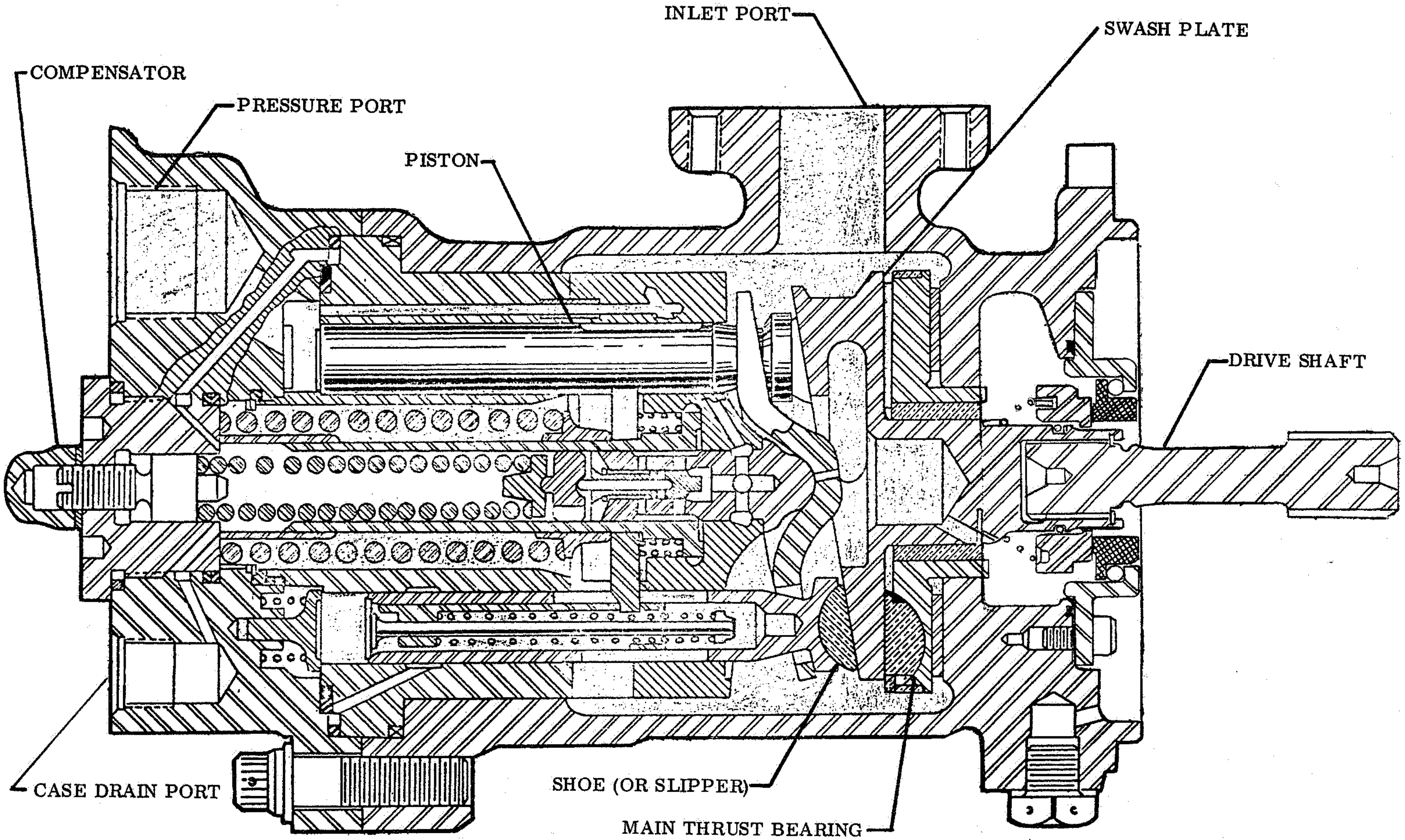

Figure 2. Cross Section of Pesco Pump Model X 013304-010

extends into each of the pistons to position the inlet valve opening. Past experiences (Refs. 2 and 3) with this pump, in the pumping of various experimental fluids (Table VII), have shown that the shoes, thrust bearings and swash plate were the prevalent sites of failure. Accordingly, the boundary lubrication tests of Task II were performed to screen suitable materials for use as pump bearings with the specific fluids.

Based on the results of the boundary lubrication tests,pump bearings were made of the following materials for use with specific fluids:

Shoes and Thrust Bearings Material	Swash Plate Material	Fluid
Pheldor 10 (iron-silicon bronze)	M-2 tool steel	F-50
S Monel (copper-nickel-silicon alloy)	M-2 tool steel	MCS-293
K-82 (tungsten-titanium carbide + 13% cobalt)	K-96 (tungsten carbide + 6% cobalt)	MLO 60-294
K-82	K-96	MCS-3104
Star J (cobalt base super alloy)	440C + 4% molybdenum	PR-143 AB

Pump break-in was accomplished by running the pump from 500 to 3000 psi in 500 psi increments. The fluid temperature rose from room temperature to about 250°F during the pressure increment rise. After the pump has been set for 3000 psi, a brief temperature excursion to 350°F to 400°F with occasional flow cycling was made. The pump was then disassembled and the critical parts measured, weighed, and documented.

The pump loop is shown schematically in Figure 3. A photograph of the two identical pump rigs and the instrument console is shown in Figure 4. The hydraulic system of each rig comprises: a reservoir, pump, filters, load valves, heat exchanger, expansion tank, and accumulator. Instrumentation includes thermocouples, pressure gages, flow meter, pressure limit switch, and torquemeter. The fluid capacity in the system proper is about 5 gallons.

Preparatory to system operation the components are steam- and ultrasonically-cleaned, rinsed with benzene and isopropyl alcohol, and dried with nitrogen. The assembled system is purged with purified nitrogen and fed with filtered and degassed fluid. The filled system is bled to remove any gas that may have been trapped in the system.

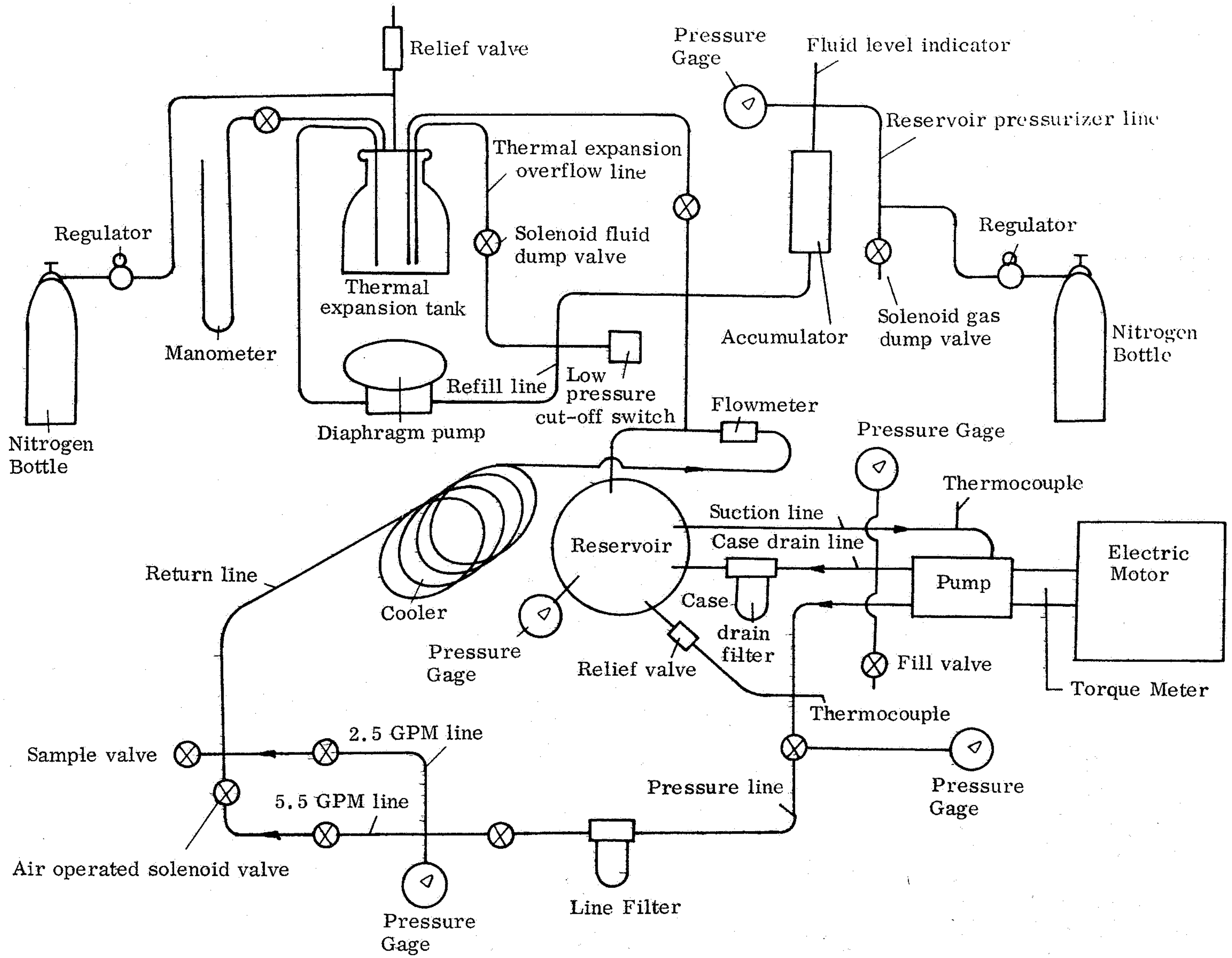

Figure 3. Schematic of Pump Rig

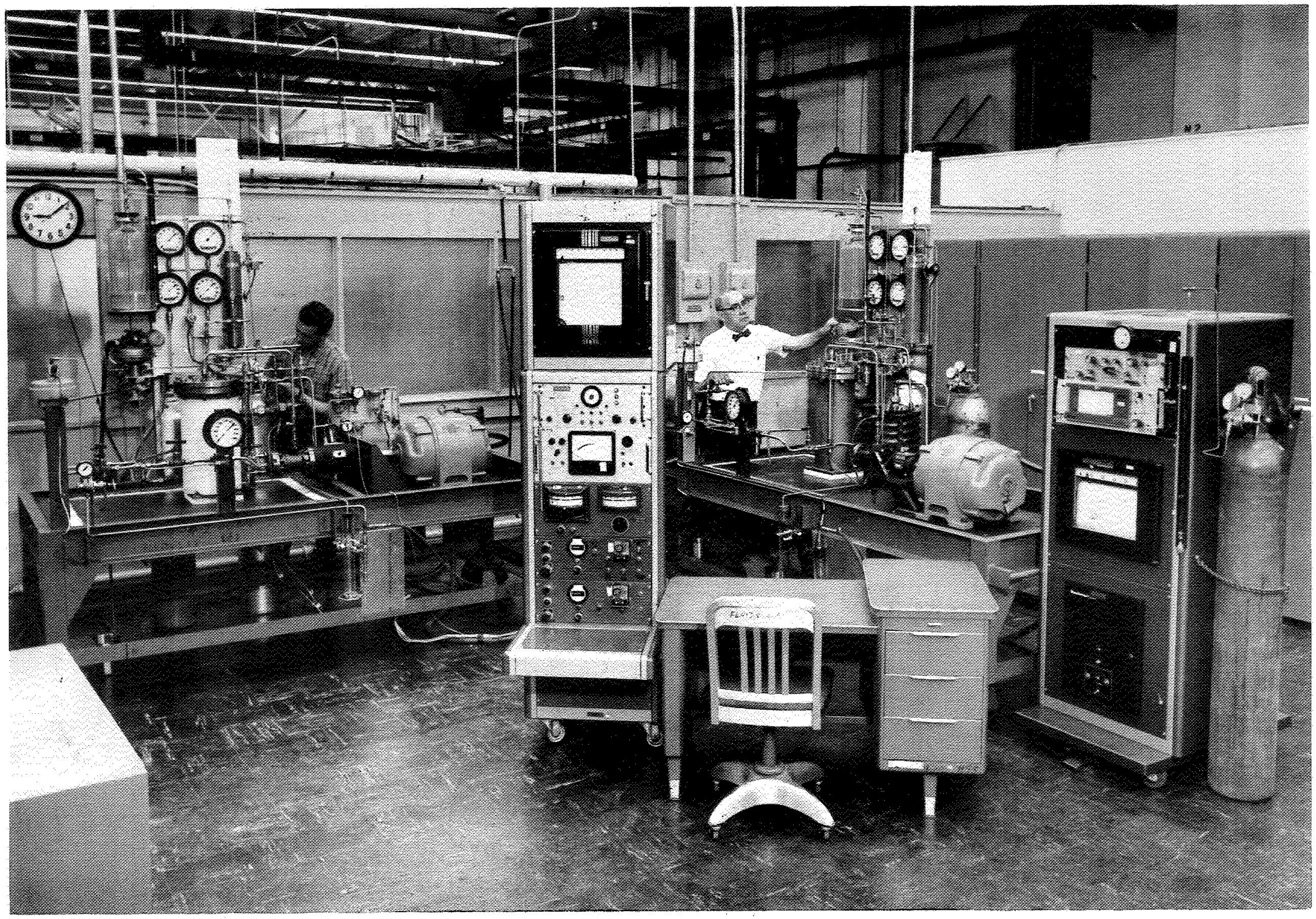

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Figure 4. Photograph of Two Pump Rigs and Instrument Console

The pump loop was normally operated at flow rates from 3 to 8 gpm during a one minute cycle at each flow rate. Pump pressure was 3000 psi. The system was operated for 50 hours at each temperature of 400°F, 500°F, and 600°F or until failure occurred. The same batch of fluid is used throughout the successive temperature runs. Fluid samples were taken from the system prior to the test, and at 5, 10, 20, 30, and 50 hours. Each fluid sample was examined for changes in viscosity and in acid number. Samples were also sent to the fluid vendor for analysis. After each test the pump was disassembled and examined for internal damage.

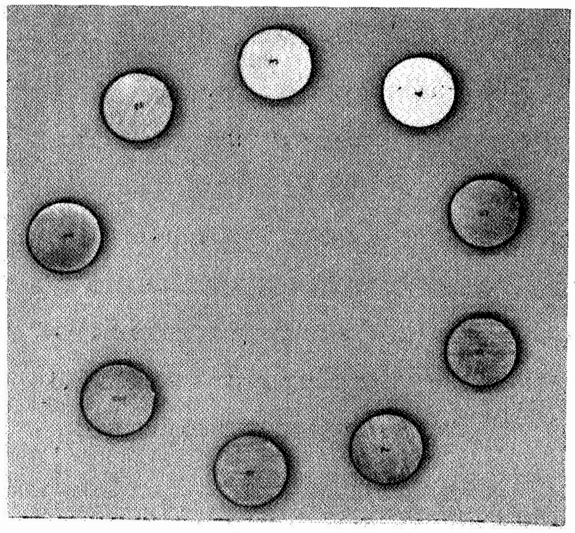
A. PUMP TESTS WITH F-50 CHLORO PHENYL METHYL SILICONE

F-50 silicone oil (lot 570) was tested with a pump containing shoes and thrust bearings made of Pheldor 10 (iron-silicon bronze) and a swash plate made of M-2 tool steel. These parts are shown in Figure 5. Height measurements of the shoes and thrust bearings are tabulated in Table I. The end clearance of the pump was measured and found to be 10.5 mils. (The end clearances of pumps subsequently tested are listed in Table VI.) During the pump break-in test it was observed that the pump compensator hunted excessively when the flow rate fell below 4 gpm. This hunting condition was later attributed to a defective spool valve.

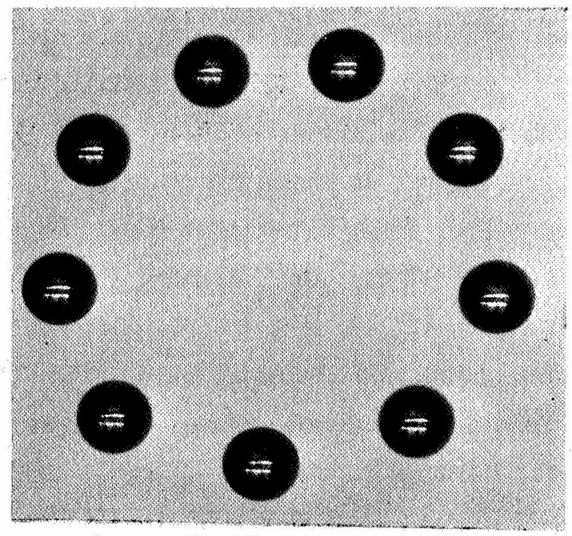
After the break-in test the pump was disassembled and inspected. Removal of the spool from the pressure compensator revealed that the lands had been chrome plated. A portion of one of the lands had a slightly rough black surface. The imperfection was probably caused during plating. The clearance between the lands and bore diameters was within 0.1 mil. The chrome plated lands were polished and the spool valve reused until a replacement was available from the vendor. The bronze shoes and bearings had slight scratch marks while the tool steel swash plate showed no visible change, Figure 6. The heights of the shoes and thrust bearings did not change, Table I.

1. 400°F Test

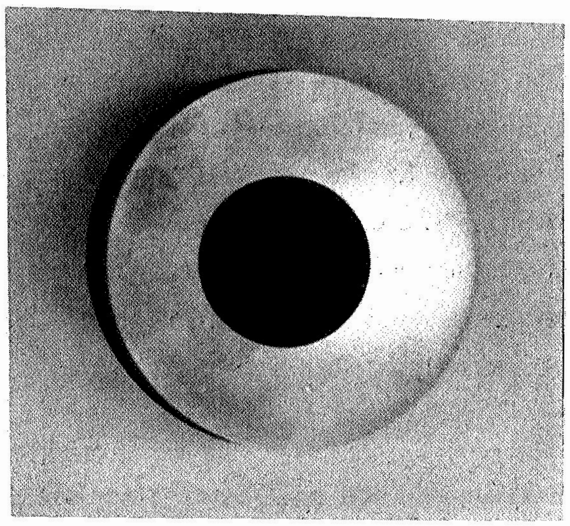
After the pump was inspected it was reassembled and installed in the system. The temperature of the fluid in the pump inlet was increased and maintained at 400°F. Frictional heat generated by the pump caused a tempera-



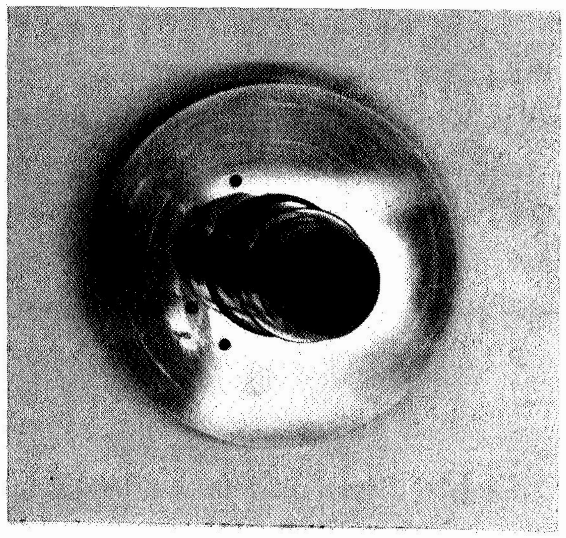
a. Shoes



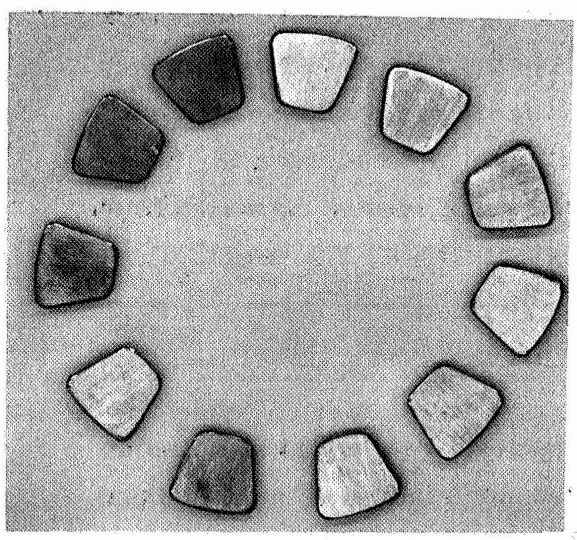
b. Shoes



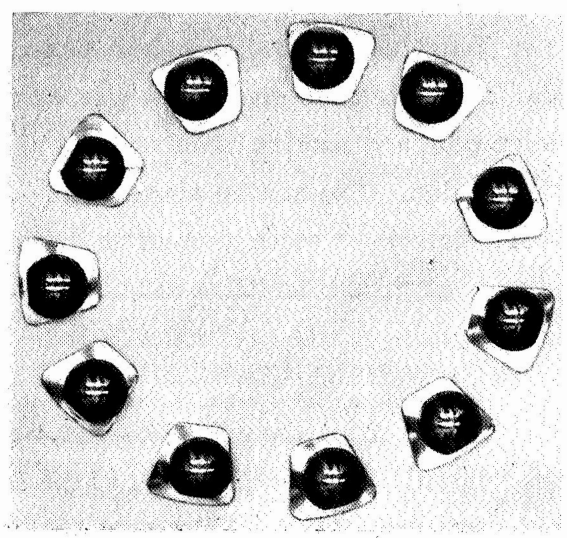
c. Swash Plate



d. Swash Plate



e. Thrust Bearings

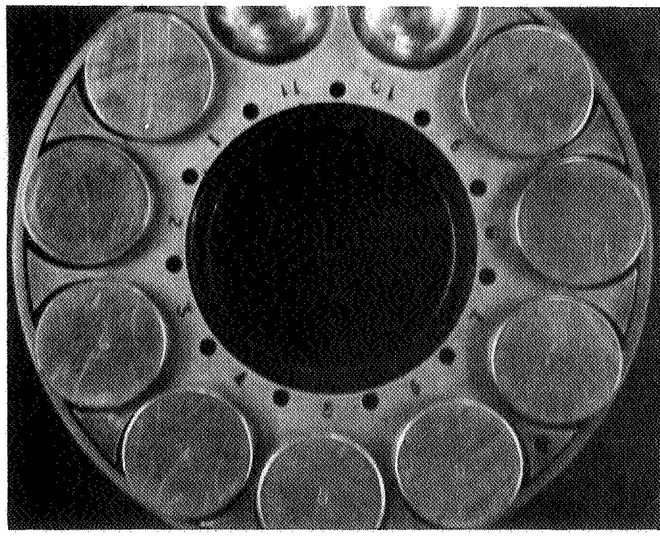


f. Thrust Bearings

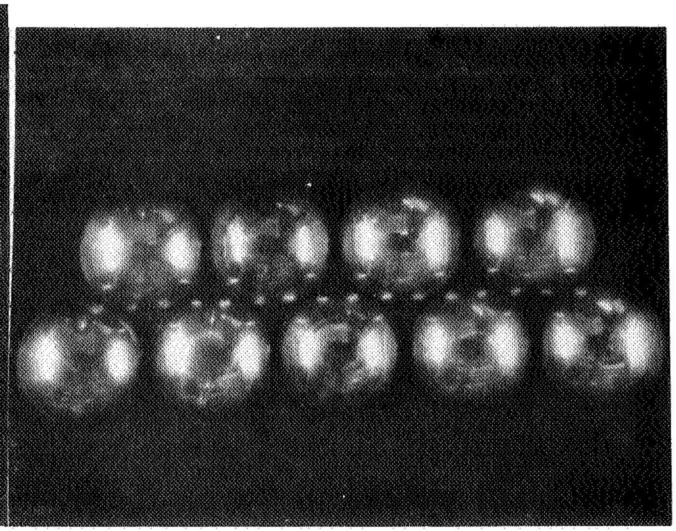
Figure 5. Pheldor 10 Shoes and Thrust Bearings and M-2 Swash Plate As Received in Pump S/N X-1803

TABLE I. - DIMENSIONAL CHANGE OF PHELDOR 10 SHOES AND THRUST BEARINGS

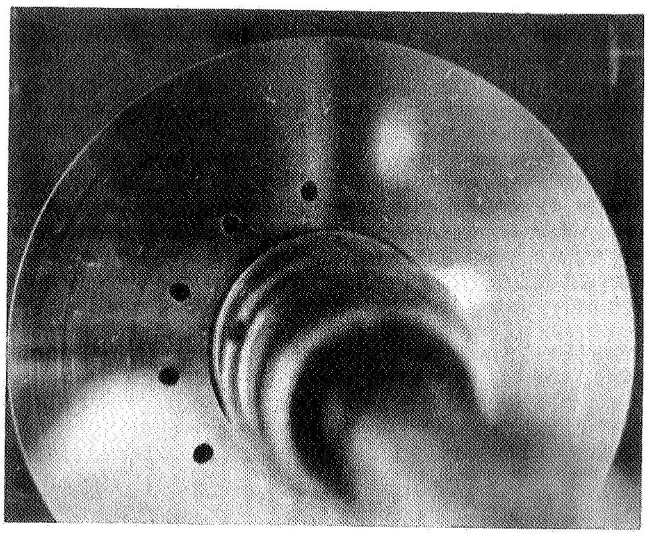
Pheldor 10 Shoes Height (Inches)							
Shoe No.	As Rec'd	After Break-in	18 Hrs. @ 400°F	50 Hrs. @ 400°F	5 Hrs. @ 500°F	2 Hrs. @ 500°F Before	2 Hrs. @ 500°F After
1	.2495	.2495	.2495	.2494	.2495	.2452	.2319
2	.2500	.2500	.2500	.2500	.2501	.2452	.2424
3	.2498	.2498	.2498	.2498	.2501	.2452	.2430
4	.2493	.2493	.2494	.2494	.2494	.2453	.2433
5	.2505	.2504	.2504	.2505	.2504	.2451	.2421
6	.2498	.2498	.2500	.2499	.2499	.2453	.2428
7	.2497	.2497	.2498	.2498	.2498	.2451	.2390
8	.2481	.2481	.2481	.2482	.2483	.2451	.2427
9	.2499	.2499	.2499	.2499	.2500	.2451	.2413
Pheldor 10 Thrust Bearings Height (Inches)							
1	.3154	.3154	.3154	.3155	.3155	.3149	
2	.3154	.3155	.3156	.3156	.3155	.3150	
3	.3150	.3154	.3153	.3154	.3153	.3148	
4	.3155	.3156	.3159	.3157	.3156	.3152	
5	.3152	.3152	.3154	.3154	.3154	.3149	
6	.3149	.3150	.3152	.3152	.3152	.3146	
7	.3154	.3156	.3157	.3158	.3157	.3151	
8	.3153	.3154	.3155	.3156	.3156	.3151	
9	.3154	.3156	.3156	.3156	.3158	.3151	
10	.3155	.3157	.3160	.3158	.3159	.3152	
11	.3153	.3154	.3155	.3155	.3155	.3149	



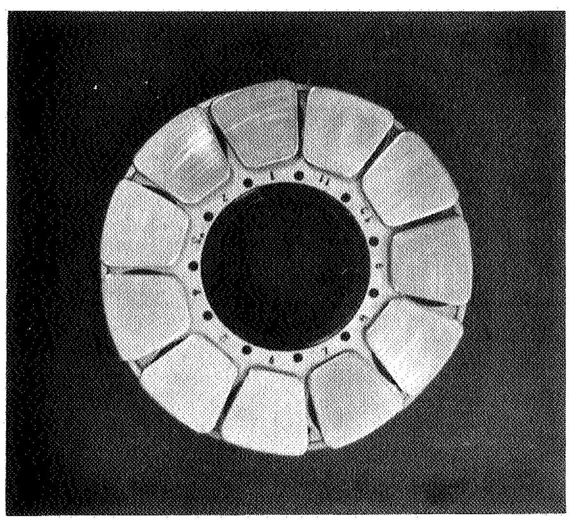
a. Shoes



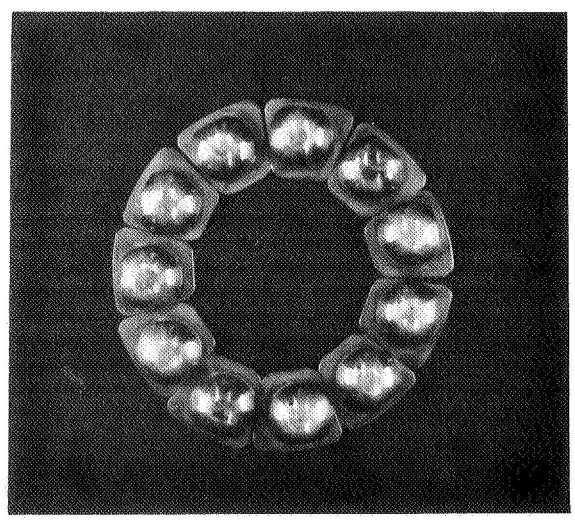
b. Shoes



c. Swash Plate



d. Thrust Bearings



e. Thrust Bearings

Figure 6. Pheldor 10 Shoes and Thrust Bearings and M-2 Swash Plate After Break-In Test With F-50 Silicone Oil

ture rise to 415°F on the discharge side of the pump. The pump was cycled from 4 to 9 gpm in one minute intervals at each flow rate. The shaft seal on the pump began to leak after 2.66 hours at 400°F. (All time periods indicated are from the start at maximum temperature.) Shaft seal leakage accumulated to 15 ml. after 8 hours. The system was shut down after 18 hours when the shaft seal leakage rate rose to 38 drops per minute (dpm). The Viton O-ring static seals of the rotary shaft seal were replaced and the test was resumed. The seal replacements afforded an opportunity to take a sample of wear debris which had collected in the cavity of the swash plate.

After 25 hours of operation the pressure drop across the pressure line filter increased to 400 psid. The shaft seal leakage rate was about 1 dpm. The test was interrupted to replace the pressure line filter element (10-micron nominal). The two static O-rings in the pump were also replaced as a precautionary measure. The test was continued until the 50-hour run at 400°F was attained. The shaft seal leakage rate at the end of the test was 60 dpm.

Fluid samples were recovered from the sample valve in the system at 0, 5, 10, 20 and 30 and 50 hours. Viscosity measurements taken at 100°F on the 5-hour sample showed a slight decrease in value below that of the unused sample. Later samples showed the viscosity had reached an equilibrium value slightly less than that of the unused sample, Figure 7. This change in viscosity is indicative of permanent fluid shear. Viscosity measurements taken at 210°F showed negligible change over the original fluid sample. Apparently the bulk of the sheared molecules had volatilized during the 210°F viscosity measurements thereby leaving the fluid viscosity unchanged. The acid number of the samples did not change during the test, Figure 7.

Copper colored particles were present in the pressure line filter element and bowl. A slight air pressure applied to the filter element indicated essentially free passage through the pores. The pressure drop across the element was attributed to the accumulation of metallic particles rather than being caused by sludging of the fluid.

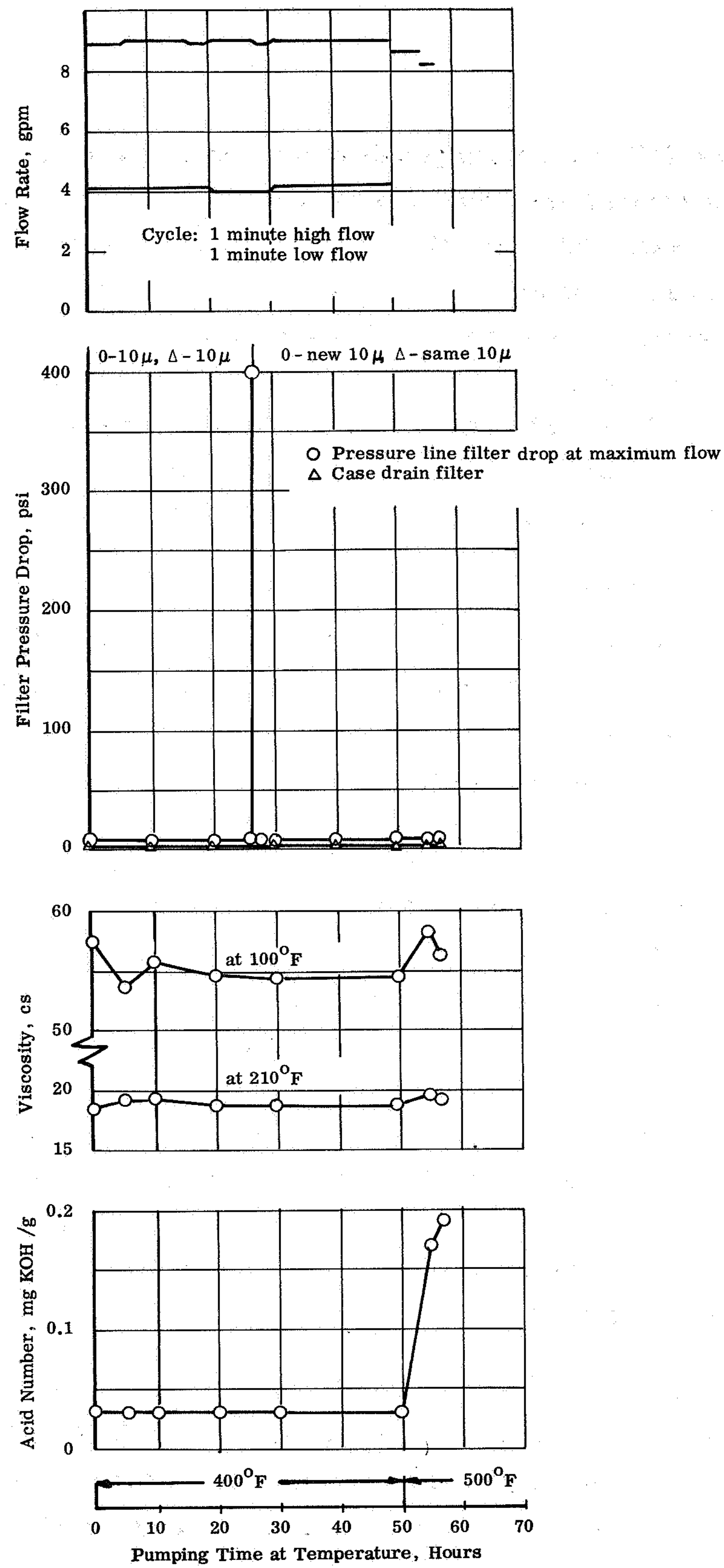


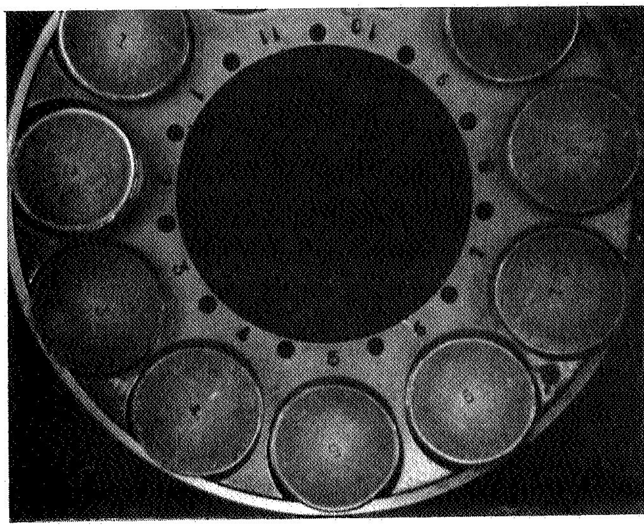
Figure 7. Flow Rate, Filter Pressure Drop, Viscosity, and Acid Number Change, During Pump Tests with Chlororhenyl Methyl Silicone

Examination of the Pheldor-10 shoes and bearings showed a color change from a light copper sheen to a dull bronze. The spherical portions of the shoes and bearings flaked in spots in thin layers, and these particles were collected by the pressure line and case drain filters, and by the cavity in the swash plate. Thin films of smeared bronze deposits were evident in some of the sockets of the pistons and in the thrust bearing retainer assembly. Polished annular rings were formed on the spherical side of the shoes where contact with the mating piston sockets was made. The flat sides of the shoes and bearings were slightly scratched. Despite these findings the critical heights of the shoes and bearings were not changed, Table I. The condition of the shoes and bearings are shown in Figure 8.

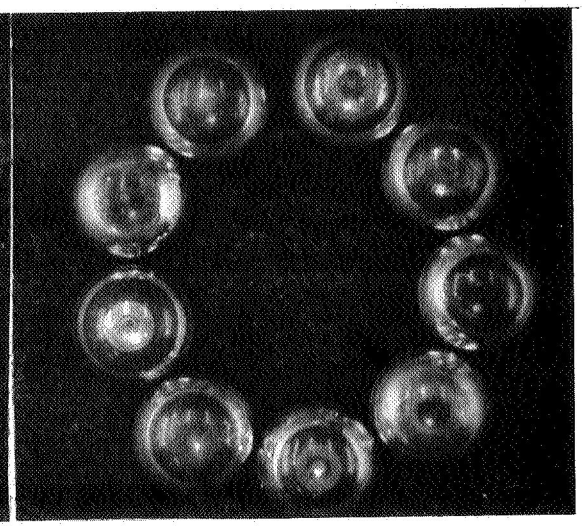
The Viton A O-ring static seal in the rotary shaft seal assembly had taken a compression set, and leakage occurred past the static seal. The faying surfaces of the metal-graphite shaft seal appeared to have a smooth wear pattern.

Using emission spectroscopy, incomplete analyses of the wear debris by the fluid vendor indicated the following. The wear debris collected from the swash plate cavity after the break-in test contained approximately 42% iron, 12% copper, and 0.05% zinc. After 18 hours at 400°F, the wear debris collected was 99.9% copper with some zinc and a trace of iron. The wear debris collected after 50 hours at 400°F from the line and case drain filters again was 99.9% copper with some zinc and a trace of iron. A portion of the wear debris still has not been identified.

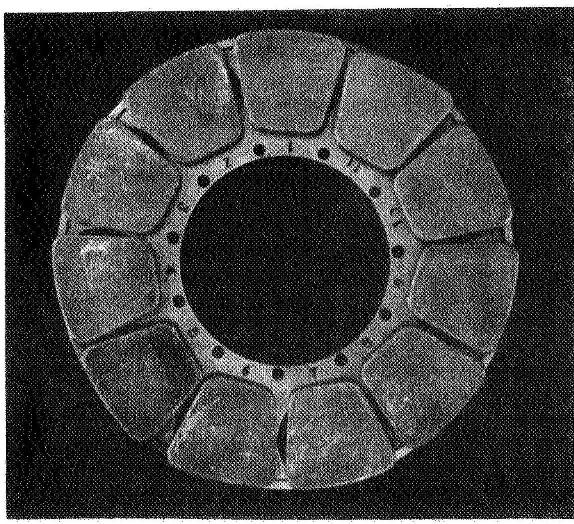
The nominal composition of Pheldor-10 is: 95.5% copper, 3.0% silicon, 1.0% manganese, and 0.5% iron. A partial emission spectroscopy analysis of the raw materials used in the fabrication of the shoes indicated 94% copper, 0.04% zinc and a trace of iron. The raw material for the thrust bearings contained 92% copper, 0.01% zinc and a slight trace of iron.



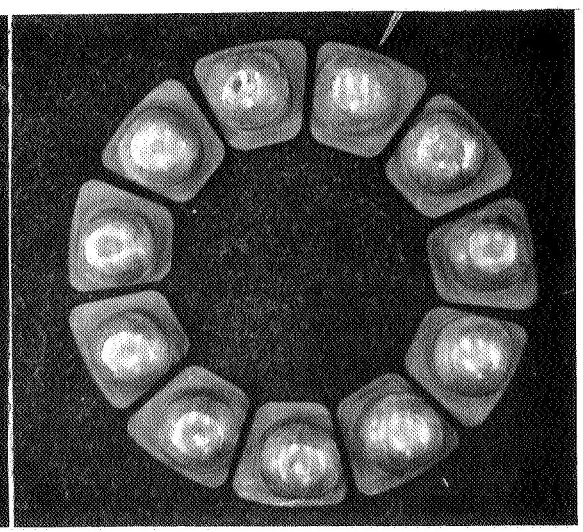
a. Shoes



b. Shoes



c. Thrust Bearings



d. Thrust Bearings

Figure 8. Pheldor 10 Shoes and Thrust Bearings After 50 Hours at 400°F With F-50 Silicone Oil

The zinc/copper ratio for the bronze shoes is 0.00046 and 0.0012 for the bronze thrust bearings. The zinc/copper ratio from the wear debris is:

break-in: 0.0047

18 hours: 0.00023

50 hours line filter: 0.00028

50 hours case drain filter: 0.0013

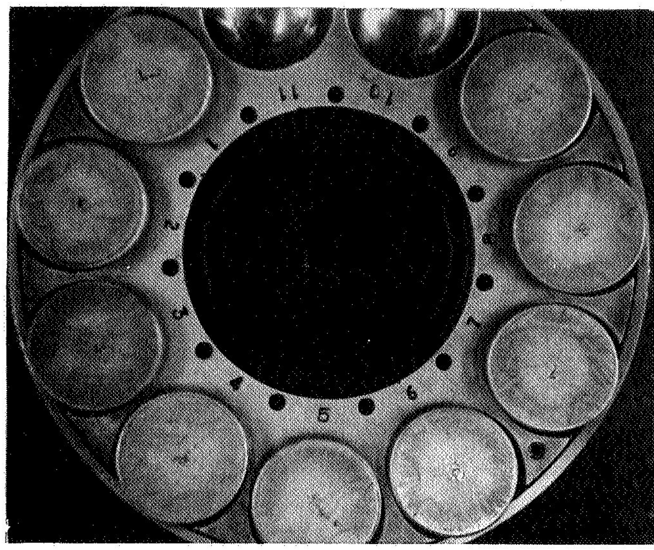
It can be seen that the initial rate of zinc removal was high and may have contributed in part to the flakiness of the bronzes. The case drain filter had not been changed during the test and was probably initially high in zinc but was continuously diluted with copper-rich debris. The line filter had been changed at the 25-hour mark.

2. 500°F Test

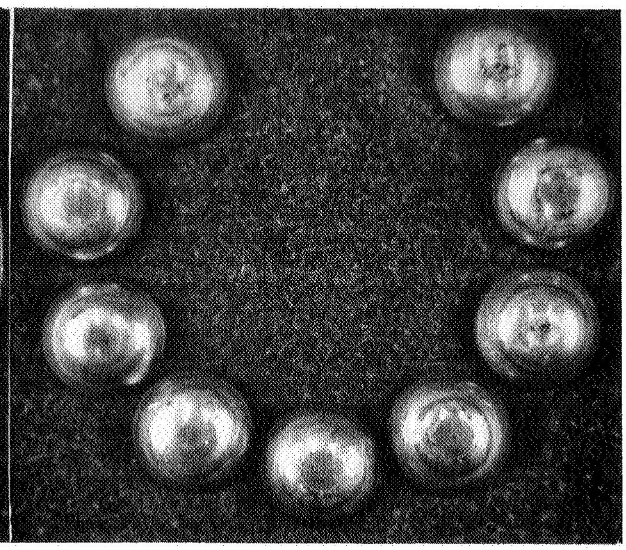
The silicone fluid was next subjected to 500°F at a constant flow rate of 8.6 gpm. Flow cycling was not continued during the 500°F test, as it had been in the previous test, because of excessive pump hunting. The test was arbitrarily stopped after 5 hours to examine the shoes and thrust bearings. The height changes of the shoes and thrust bearings were negligible,as shown in Table I. Weight measurements were taken but the accuracy was questionable.

Most of the weight loss appeared to come from the spherical side of the shoes. Shiny circular bands were visible on the spherical portion of the shoes, Figure 9, where contact between the piston socket and shoe occurred. Dull and thin flaky films, which were easily dislodged and crumbled, were also evident. A slight rim was formed on the spherical edges of some of the shoes. This deformation was caused by the impact of the piston socket shoulder against the shoe.

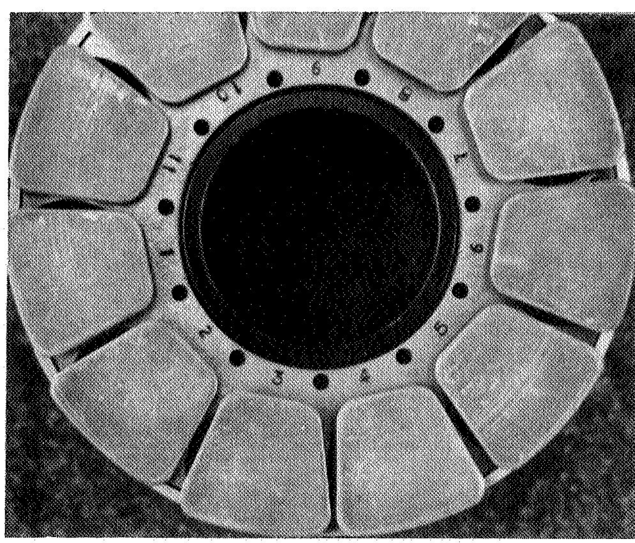
The flat sides of the shoes were less affected. The stamped numbers on the flat side of the shoes were still visible. Shoe number 6 of Figure 9a shows shiny particles radiating outward from the center. The stamped number is partially obscured by the overlaying particles. Also noticeable on the flat side of the shoes are lines in the shape of a "V" with the angle of the V pointing towards the center. The center portion appears lighter in color than the outer edges.



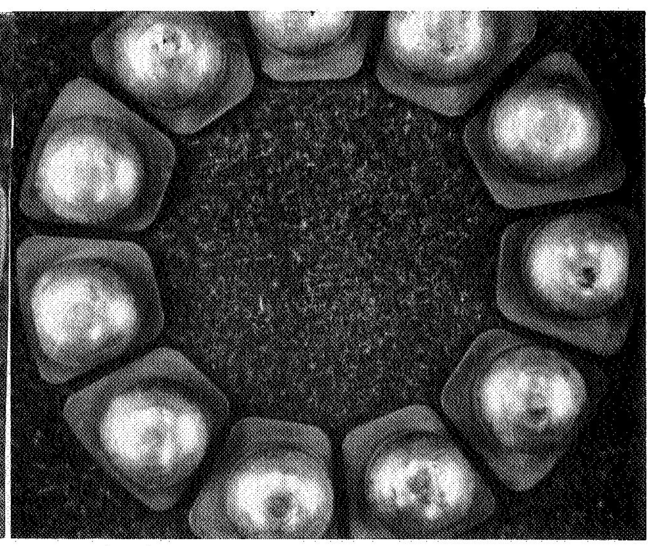
a. Shoes



b. Shoes



c. Thrust Bearings



d. Thrust Bearings

Figure 9. Pheldor 10 Shoes and Thrust Bearings After 5 Hours at 500°F With F-50 Silicone Oil

It is speculated that the fluid between the shoe and swash plate is compressed and decompressed during the rotation of the swash plate. This is suggested by the shaded color and dark V lines. During the abrupt pressure changes the contour of the flat side is also believed to change. This change would start just before and after the top stroke of the swash plate. The radiating particles embedded on shoe number 6 are believed to have formed on this shoe because of the smaller clearance of this piston-and-shoe combination and the swash plate. The clearance is in the order of the particle sizes collected. The radiating star effect of the particles may be explained by the tilting of the shoe and the wedging of the particles along the diametral axis just before the shoe is compressed on the top stroke. This process may be repeated with the shoe rotating with the particles wedging along a different diametral axis.

Flaking with resultant particle generation also occurred on the spherical portion of the thrust bearings, Figure 9. A thin film of smeared bronze was visible in the mating part of some thrust sockets. The flat side of the bearings turned to a dark, dull, brown-copper color. Some shiny particles of bronze are shown along the trailing edge of thrust bearing number 11, Figure 9. This indicates essentially effective hydrodynamic lubrication between the thrust bearings and the swash plate by the silicone oil at 400° F. The hardness of the new shoes and thrust bearings were VHN 203 and VHN 151, respectively; however, after 5 hours at 500°F the hardness changed to VHN 238 and VHN 176, respectively.

The viscosity of the fluid increased during the 5-hour period at 500°F, Figure 7. The rise in viscosity was probably caused by the fluid shearing, cross-linking, and evaporation of the more volatile products. The acid number increased from 0.03 to 0.17 mg KOH per gram of fluid.

Fretting corrosion in the form of a reddish-brown mud occurred on the spline of the drive shaft.

A <u>second test at 500°F</u> was continued with the same batch of F-50 silicone oil. The pump rig was cleaned, and the system filled with filtered, degassed oil. Another spool valve assembly was placed in the pump. The same shoes, thrust bearings, and swash plate were used as in the preceding test. However the cylinder block assembly and pistons were changed. The change was necessitated by a fracture in the neck of the pump cylinder block noticed during the previous disassembly. The end clearance of the pump was measured and found to be 11 mils. The pump inlet fluid temperature reached 500°F after 1 hour and 20 minutes. Flow cycling was from 2.7 to 8.5 gpm. Compensator hunting had disappeared. After 5 minutes at temperature the pump shaft sheared.

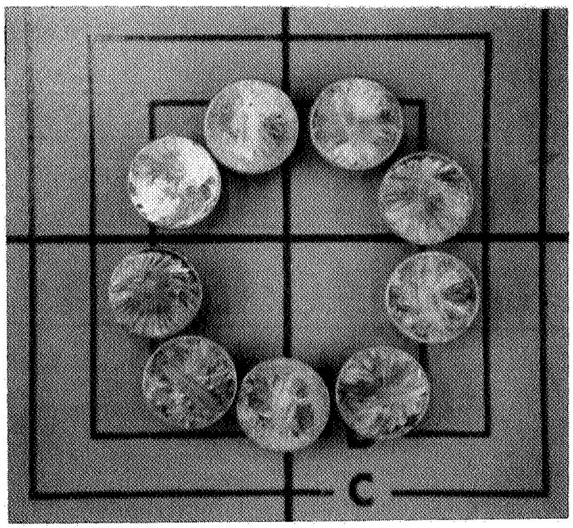
Torque overload was apparently caused by excessive particle generation and smearing, resulting in high sliding friction between the shoes and swash plate. The flat sides of the shoes were noticeably deformed, Figure 10a. Rotating smears were still evident on some of the shoes. The deformed material tends to build up in the center of the shoe. A broad smear through the diametral axis is clearly shown on one of the shoes. The spherical sides of the shoes, being the softer material, were pounded to conform to the piston sockets. The shoe rim therefore became thinner. The shoe edges were rough due to particle wedging at the leading edges. As indicated in Table II the loss in shoe material was 2 to 3 order of magnitude greater than that of the bearing material.

The fluid film between the thrust bearings and swash plate was probably thinner than in the preceding test. This is based on the presence of small entrapped particles over the entire surface of the thrust bearings. Whereas in the 400°F test, particles were only found on the trailing edge.

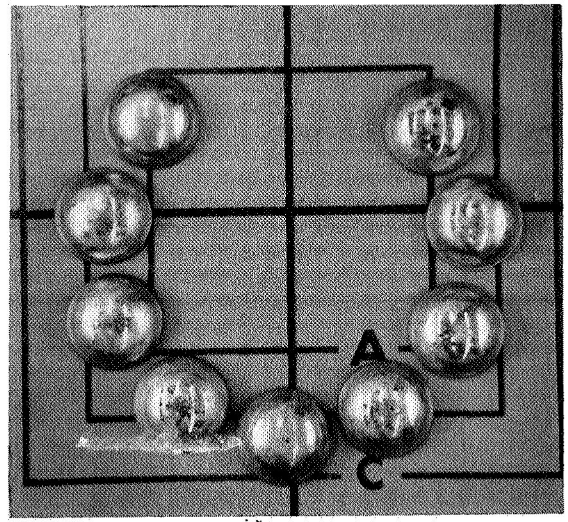
The outlines of the thrust bearings are visible on the swash plate, Figure 10d. The formation of the outlines is believed to be caused by crevice corrosion after shutdown at 500°F. On the opposite face of the swash plate, Figure 10c, copper smeared and charred fluid deposits are shown. The oxide coating of the M-2 tool steel swash plate is also believed to have been altered. Formerly, the M-2 tool steel had resisted rusting while stored for months when exposed to the atmosphere. However, it was noted that the swash plate after the 5-hour test at 500°F had rusted within hours after having been with benzene and isopropyl alcohol.

'TABLE II - WEIGHT CHANGE PHELDOR 10 SHOES AND THRUST BEARINGS

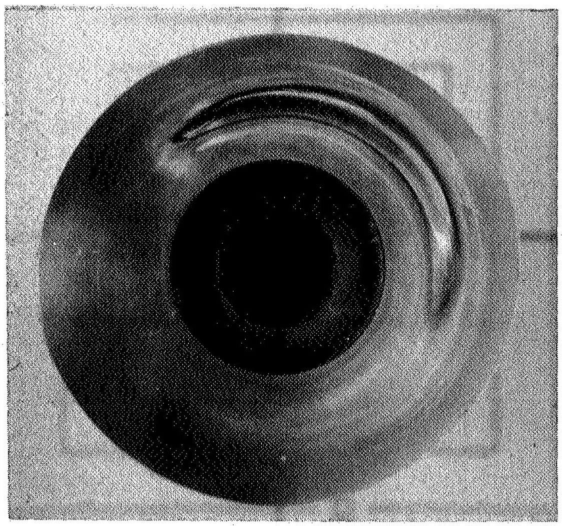
	5 Minutes @ 500°F		2 Hours @ 500°F	
Shoe No.	Weight Before, g	Weight Change, mg	Weight Before, g	Weight Change, mg
1	7.7975	- 127.2	7.5952	- 525.0
2	7.8143	- 34.2	7.5592	- 67.6
3	7.8809	- 47.7	7.6276	- 37.3
4	7.8446	- 26.6	7.6114	- 41.1
5	7.8351	- 117.9	7.5742	- 58.0
6	7.8128	- 18.9	7.5971	- 48.8
7	7.8272	- 48.1	7.5828	- 178.1
8	7.7525	+ 115.9	7.5828	- 35.9
9	7.8405	- 69.8	7.5734	- 76.0
Thrust Bearing No.				
1	10.8843	- 0.2	10.8527	- 0.8
2	10.9152	- 0.2	10.9047	- 0.4
3	10.8746	- 0.1	10.8654	- 0.3
4	10.9109	- 0.4	10.9008	0
5	10.8662	- 0.1	10.8562	- 0.2
6	10.8696	- 0.3	10.8607	0
7	10.8959	0	10.8858	- 0.7
8	10.8847	- 0.3	10.8762	+ 0.5
9	10.9045	0	10.8945	- 0.1
10	10.9021	0	10.8916	- 0.4
11	10.8825	+ 0.1	10.8675	- 0.3



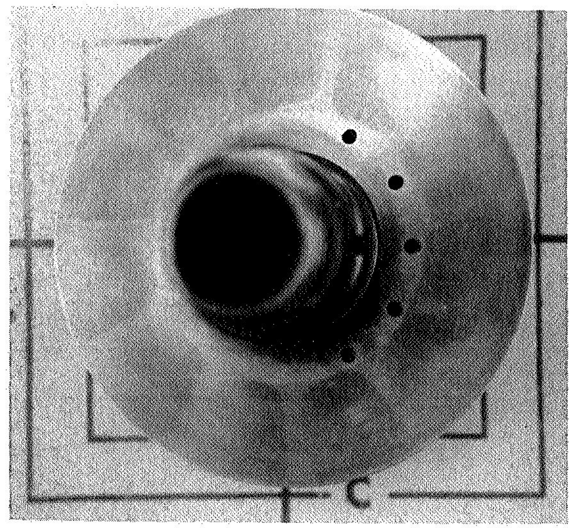
a. Shoes



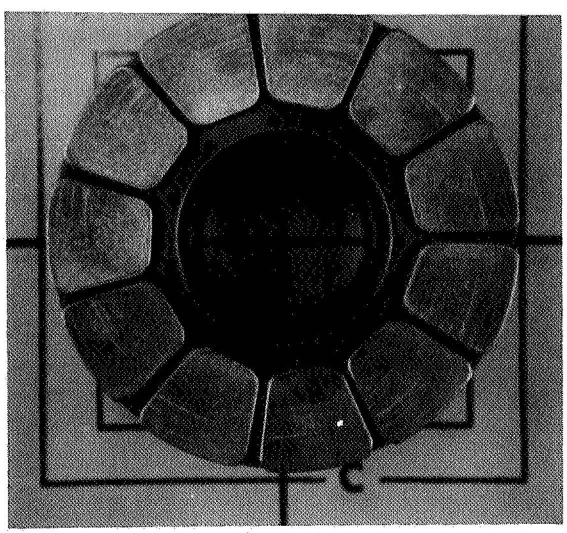
b. Shoes



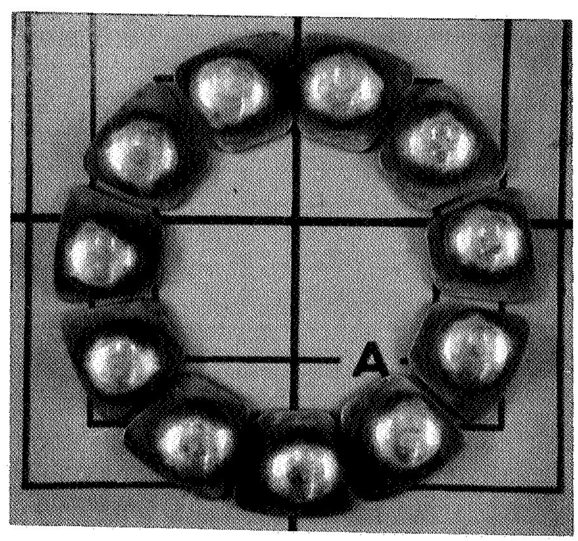
c. Swash Plate



d. Swash Plate



e. Thrust Bearings



f. Thrust Bearings

Figure 10. Pheldor 10 Shoes and Thrust Bearings and M-2 Swash Plate After 5 Minutes at 500°F With F-50 Silicone Oil

The third test at 500°F was in operation only 2 hours before the pump drive shaft sheared. Prior to this test the shoes, bearings, and swash plate had been polished to remove all scuff marks and to make all the shoes and bearings uniform in height, Table I. The pump end clearance was adjusted to 10.5 mils. Pump failure appeared similar to the preceding test. Bronze smearing on the bearings as well as on the swash plate is evident in Figure 11. Weight and height changes in the shoes and thrust bearings are listed in Tables I and II. The viscosity and acid number after this test changed as indicated in Figure 7.

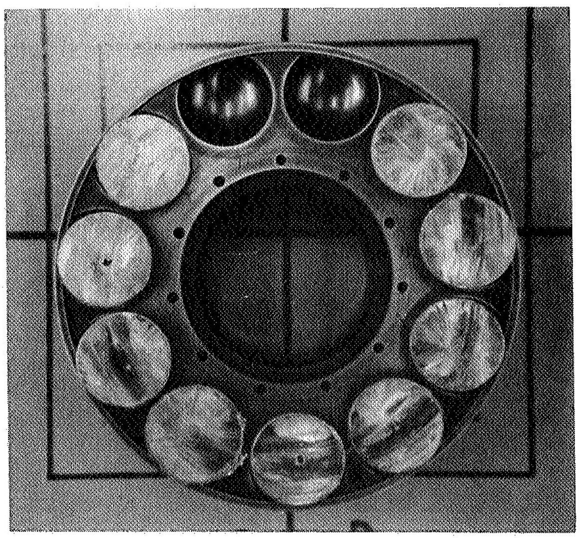
B. PUMP TEST WITH MCS-293 MODIFIED POLYPHENYL ETHER

The pump which was used in the test with MCS-293 fluid contained S Monel shoes and thrust bearings and an M-2 tool steel swash plate. Photographs of these parts, as received in pump S/N X-1802, are contained in Figure 12. Three of the cast S Monel shoes contained blow holes, which are visible in Figure 12a. Scratch marks on both sides of the swash plate were present, Figures 12b and 12c. These scratches were removed by the vendor before the pump was tested. The pump had a measured end clearance of 9 mils, which fell within the end clearance specification of 9 to 11 mils.

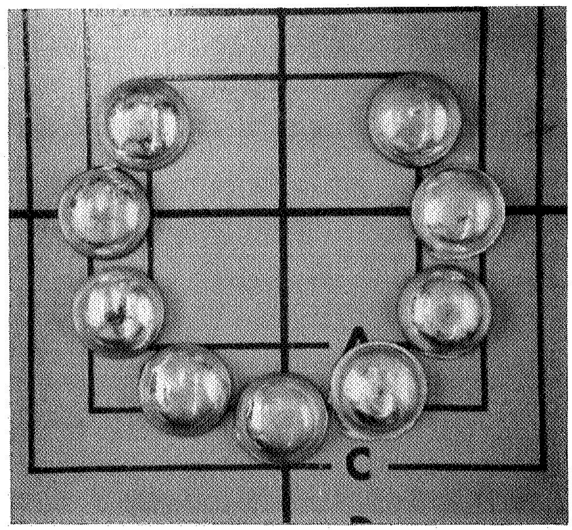
Prior to the pump break-in test the system had been cleaned and purged with purified nitrogen gas. Filtered and degassed MCS-293 was pressure-fed into the system through the fill port, Figure 3. The system was also bled to remove any entrapped gas.

The break-in run started at a pressure of 1000 psi for 10 minutes. The pump pressure was increased in 500 psi increments to 3000 psi. After the 3000 psi level was attained, the pump was flow cycled from 2 to 8 gpm with no signs of pump hunting. Operation of the pump during the test appeared smooth. The discharge flow temperature in the system was then gradually increased. When the temperature reached 350°F, the test was terminated as the torquemeter indicator started to flicker. The running time from startup to shutdown was 1 hour and 54 minutes. During the test, fluid temperature differential across the pump was within 10°F. In comparison with pump tests with other fluids this temperature differential was not considered abnormal.

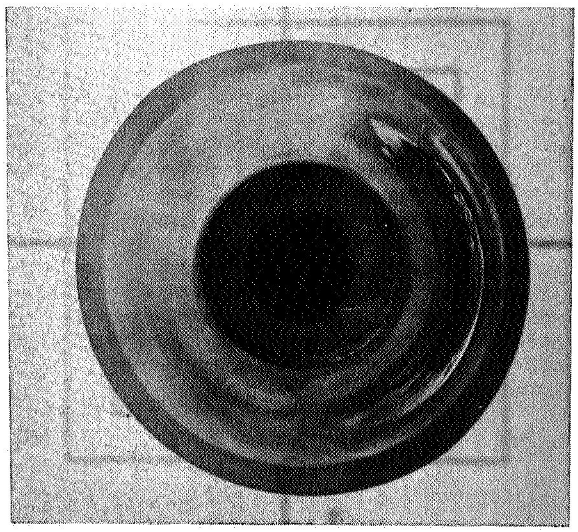
Upon examination of the pump it was revealed that the flat sides of the swash plate and of the thrust bearings had been badly scored, Figures 13d and



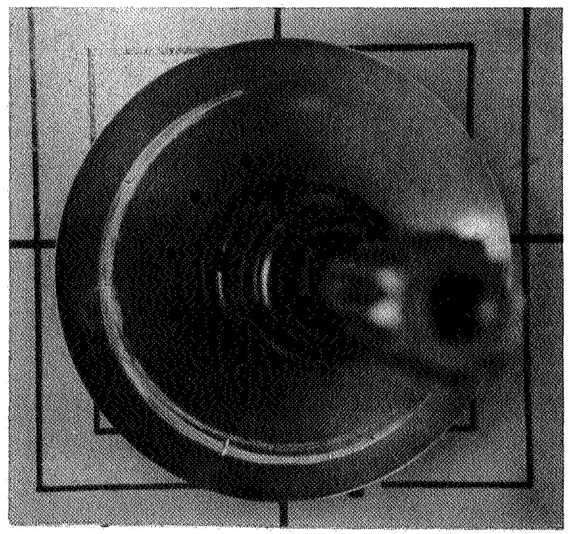
a. Shoes



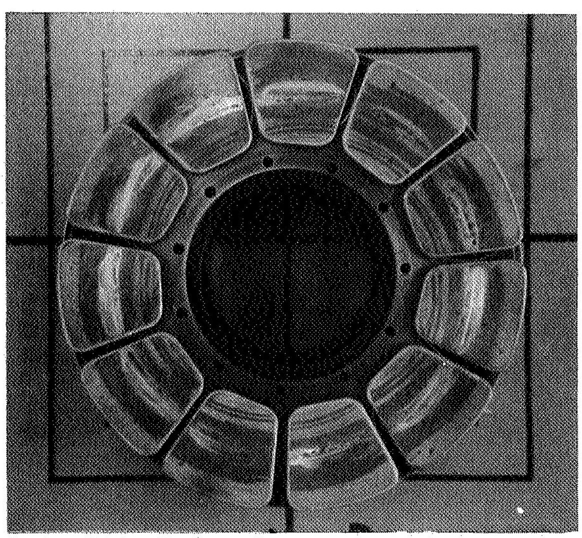
b. Shoes



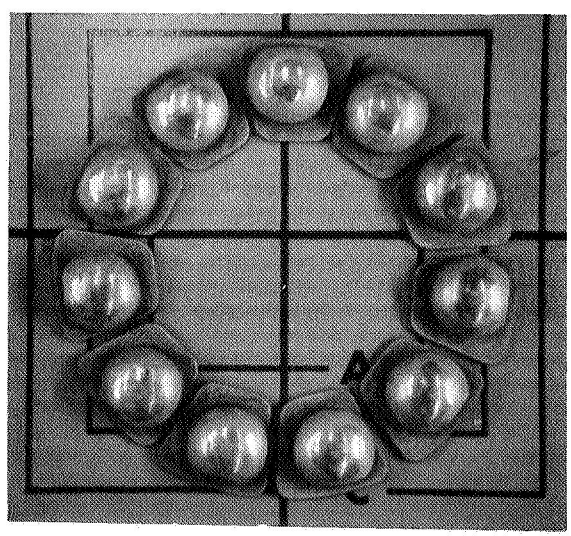
c. Swash Plate



d. Swash Plate

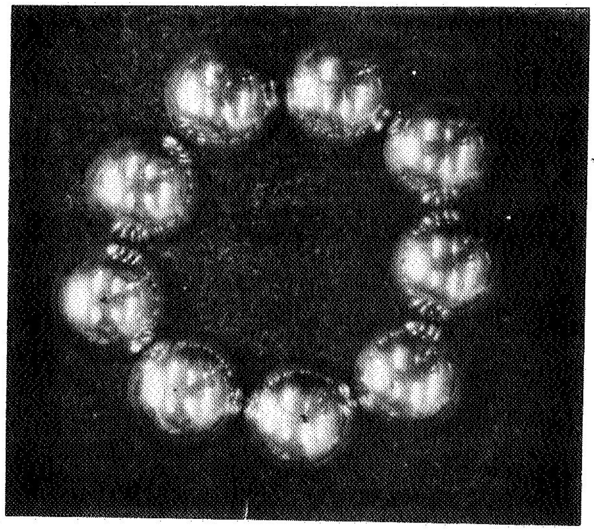


e. Thrust Bearings

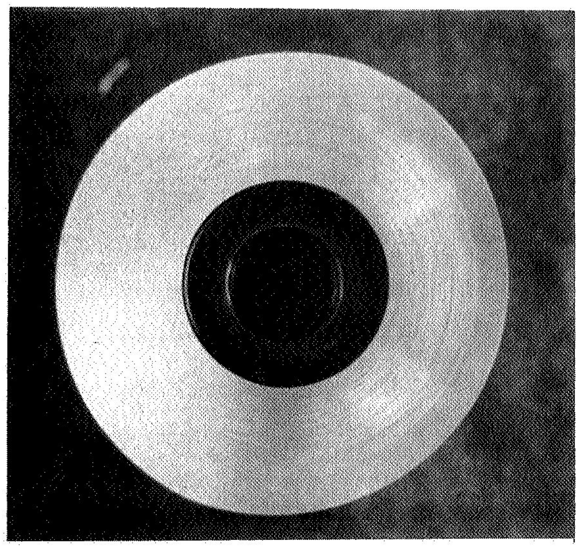


f. Thrust Bearings

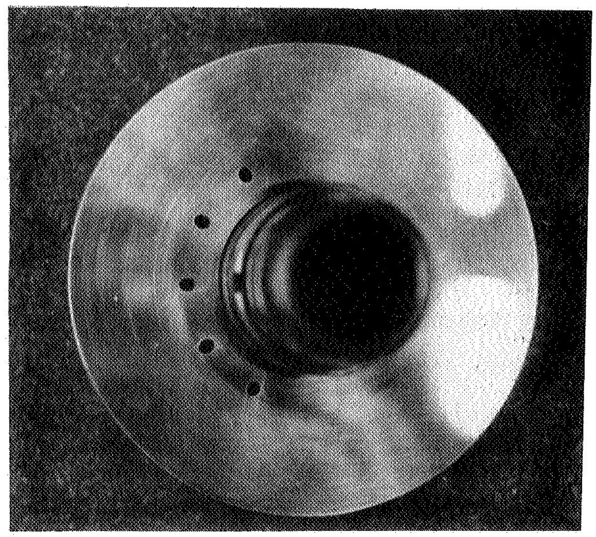
Figure 11. Pheldor 10 Shoes and Thrust Bearings and M-2 Swash Plate After 2 Hours at 500°F With F-50 Silicone Oil



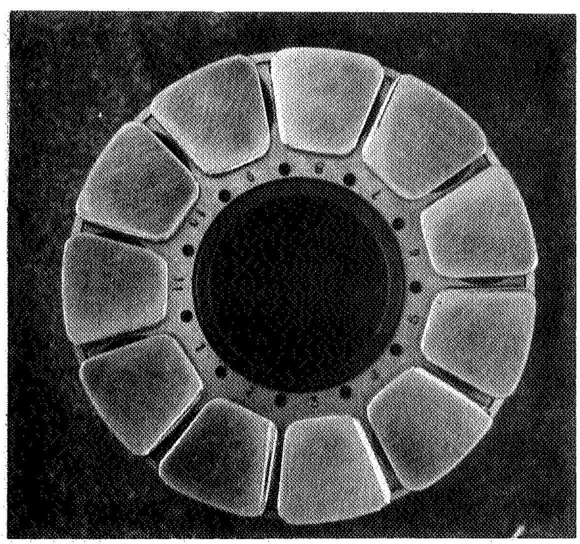
a. Shoes



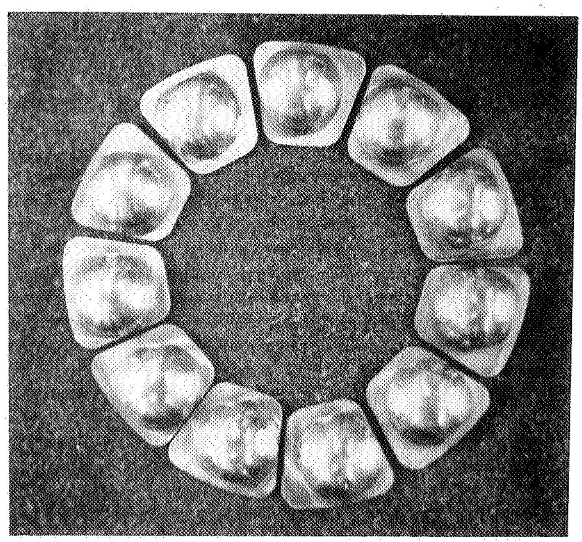
b. Swash Plate



c. Swash Plate



d. Thrust Bearings



e. Thrust Bearings

Figure 12. S Monel Shoes and Thrust Bearings and M-2 Swash Plate As Received in Pump S/N X-1802

13e. It appeared that the bearings had been riding flat on the swash plate under boundary lubrication conditions. Discoloration of the bearings and swash plate was indicative of the intense heat that had been generated. Smearings of S Monel and charred fluid were found on both sides of the swash plate. Negligible change in shoe and bearing height was measured, Table III. The total bearing weight loss was about three times the shoe loss. Little, if any, surface changes on the spherical portions of bearings were observed. Whereas the thrust bearings had been badly scored the shoes appeared in good condition. The fluid had a sulfurous odor and appeared darker in color. Fluid decomposition products were caused by local hot spots at the bearings. The viscosity and acid number of the fluid was unchanged.

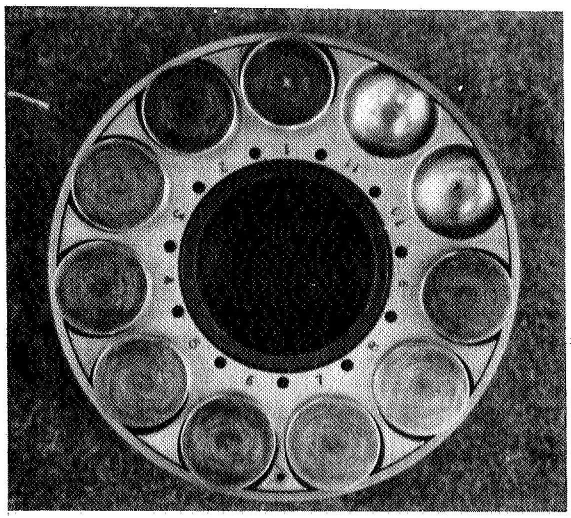
	Viscosity @ 100°F, cs	Viscosity @ 210°F, cs	Acid Number, mg/KOH/g
Fresh fluid	25.30	4.18	.01
Break-in fluid	25.32	4.09	.05

Preliminary analysis of the debris collected from the line filter indicated the presence of iron, mickel and copper as the major constituents with molybdenum, chromium, and vanadium present in minor amounts. These are the same elements present in S Monel and M-2 tool steel. The fluid may have been the source of the phosphorous and sulfur detected. The hardness of S Monel material was Rc 37 while the hardness of the tool steel swash plate was Rc 58.

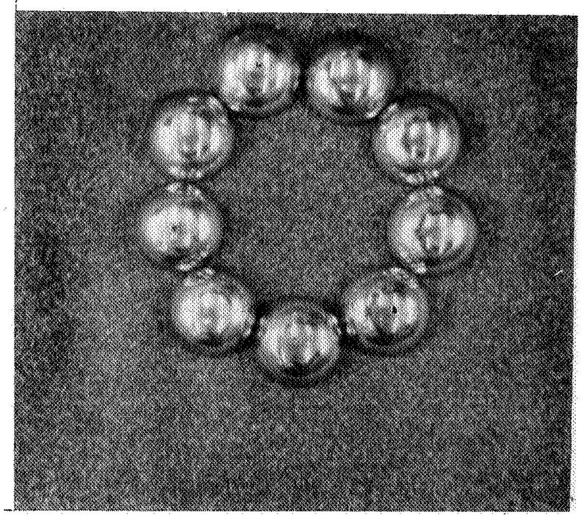
Lubrication of the thrust bearings and swash plate was not effective. The S Monel material smeared on the swash plate during marginal lubrication conditions. It is believed that the transfer of S Monel back to the bearings resulted in the removal of M-2 tool steel particles from the swash plate. Once tool steel particles were formed the wear process accelerated to the condition shown in Figure 13.

C. PUMP TESTS WITH MLO 60-294 DEEP DEWAXED MINERAL OIL

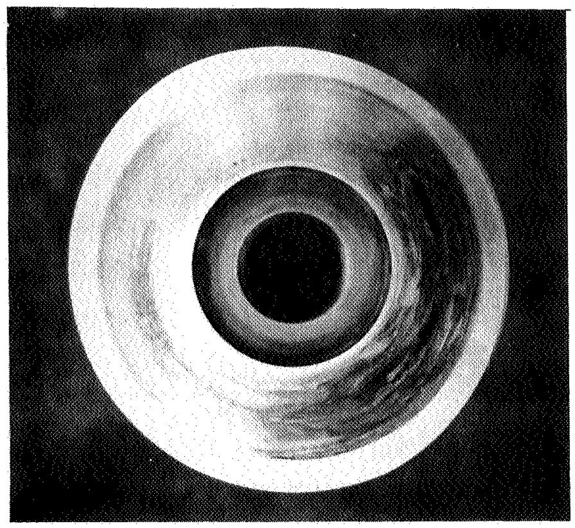
The deep-dewaxed mineral oil was tested with a pump containing K-82 (tungsten-titanium carbide + 13% cobalt) shoes and thrust bearings and K-96 (tungsten carbide + 6% cobalt) swash plate. These parts were photographed,



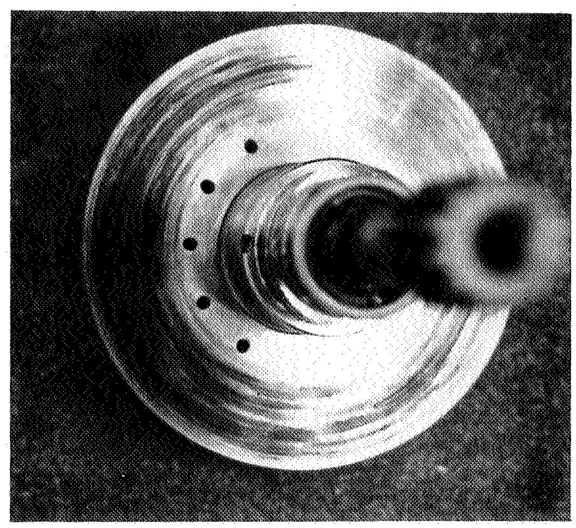
a. Shoes



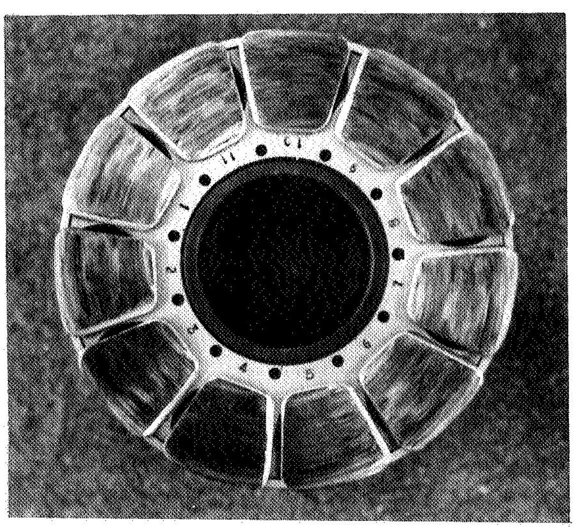
b. Shoes



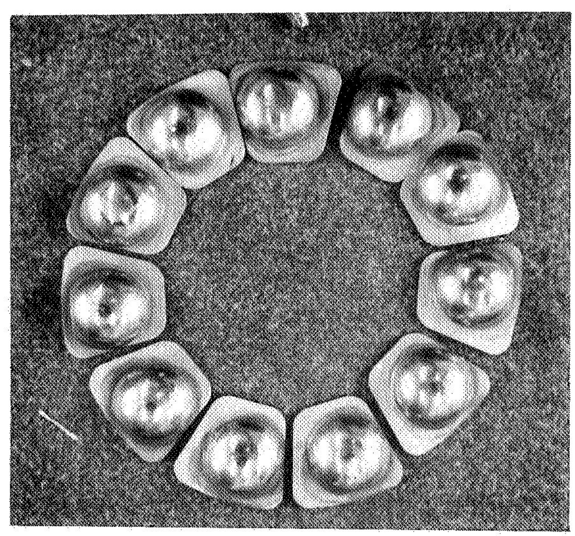
c. Swash Plate



d. Swash Plate



e. Thrust Bearings



f. Thrust Bearings

Figure 13. S Monel Shoes and Thrust Bearings and M-2 Swash Plate After Break-In Test With MCS-293 Modified Polyphenyl Ether

TABLE III - HEIGHT AND WEIGHT CHANGE OF S MONEL SHOES AND THRUST BEARINGS

Weight Change (Grams)			Height Change (Inches)	
S Monel Shoes				
Shoe No.	As Received	After Break-in	As Received	After Break-in
1	7.7627	-.0142	.2485	-.0007
2	7.7294	-.0144	.2478	-.0005
3	7.6261	-.0130	.2469	-.0008
4	7.6054	-.0021	.2473	-.0006
5	7.6970	-.0170	.2471	-.0005
6	7.5496	+.0016	.2467	-.0007
7	7.6899	-.0138	.2470	-.0006
8	7.6505	-.0142	.2468	-.0007
9	7.6578	-.0111	.2464	-.0006
S Monel Bearings				
1	10.8028	-.0958	.3128	-.0004
2	10.9057	-.0313	.3148	-.0006
3	10.8152	-.0235	.3135	-.0003
4	10.8426	-.0335	.3142	-.0005
5	10.8874	-.0354	.3142	-.0005
6	10.9366	-.0317	.3153	-.0005
7	10.8634	-.0331	.3134	-.0005
8	10.8134	-.0347	.3130	-.0005
9	10.8917	-.0219	.3145	-.0002
10	10.9794	-.0266	.3153	-.0003
11	10.8528	-.0167	.3141	-.0003

Figure 14, as received in pump S/N X-1800. Small fractures occurred during broaching of the spline, Figure 14c, and during the drilling of the lubrication holes in the swash plate, Figure 14d. The material of the swash plate is very brittle and easily susceptible to chipping at sharp edges or corners.

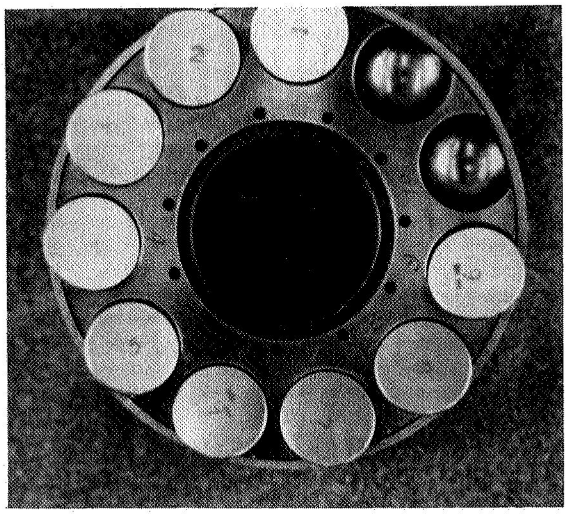
The pump break-in run was terminated shortly after startup because of severe pump vibration. The vibration was caused by an unbalanced swash plate. The swash plate was returned to the vendor for balancing. The swash plate after balancing is shown in Figure 15. After the break-in test with the balanced swash plate, three cracks in shoe number 3 were detected, Figures 16a and 16c. The sharp edges of the cracks were filed smooth with a diamond dust file and the shoe was reused as shown in Figure 17. The cracks in the shoe are believed caused by high localized stresses induced at burred or sharp edges.

1. 400°F Test

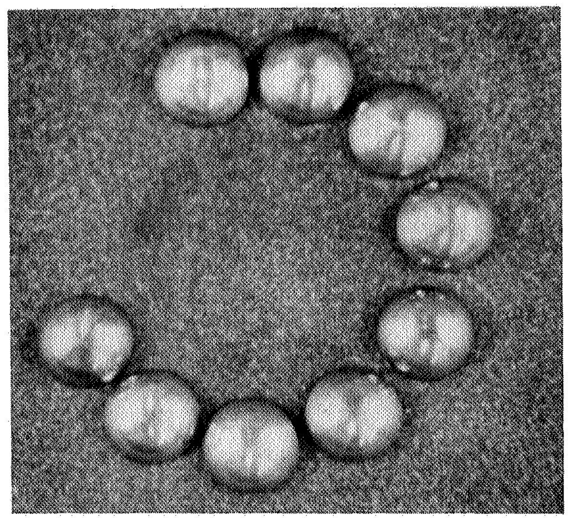
The mineral oil was heated to 400°F pump inlet temperature and cycled at 2.6 to 8.2 gpm. The test was run continuously for 50 hours without shutdown. The total shaft seal leakage during the test was one milliliter. A metallic rubbing noise was heard during flow cycling. This noise was later attributed to the pump pressure compensator springs, Figures 18 and 19, rubbing against the housing walls, Figure 2. The shoes, thrust bearings, and swash plate after the test were observed to be in excellent condition, Figure 20. Changes in weights and heights of the shoes and bearings were negligible, Table IV. No significant changes in viscosity and acid number of the mineral oil were measured, Figure 21.

2. 500°F Test

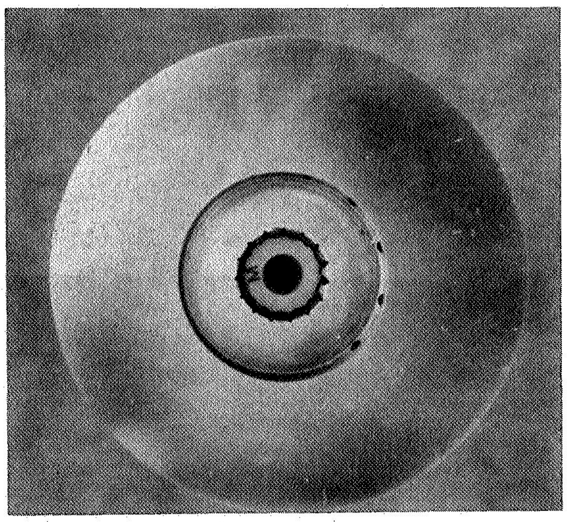
During the 50-hour run at 500°F the test was stopped three times to make several repairs. The test was first interrupted after 7.4 hours when a leak developed in the welded fitting connecting the relief valve to the reservoir and in the brazed fitting which joins the pressure gage line to a valve in the pressure side of the system. Shaft seal leakage up to this time was about 1 ml. The test was resumed after the necessary repairs were made. The test was stopped a second time at the 20-hour mark because of a 75 psi pressure drop across the case drain filter (rated at 10-micron nominal). Compensator spring wear is



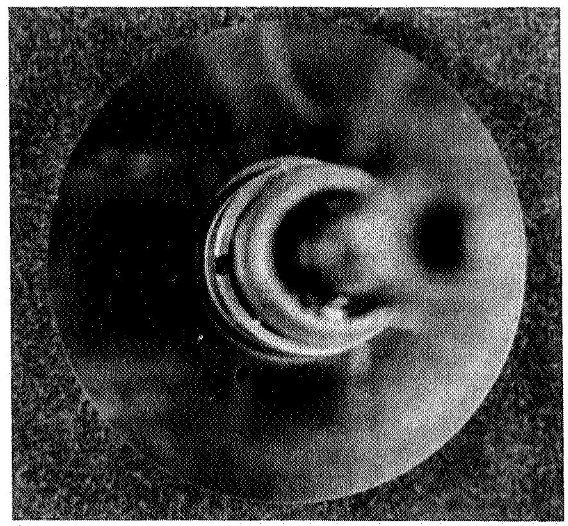
a. Shoes



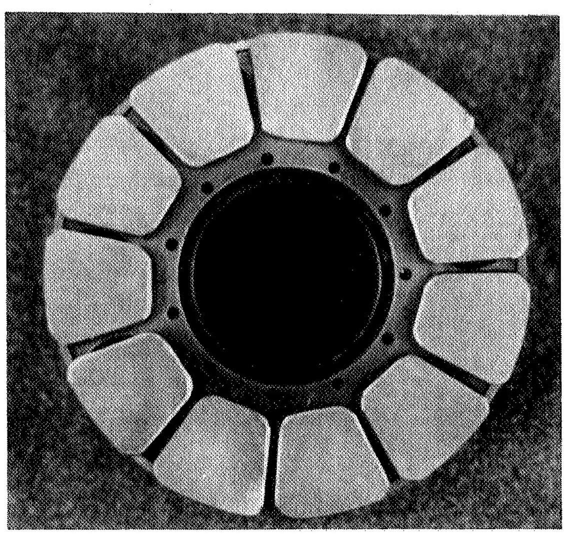
b. Shoes



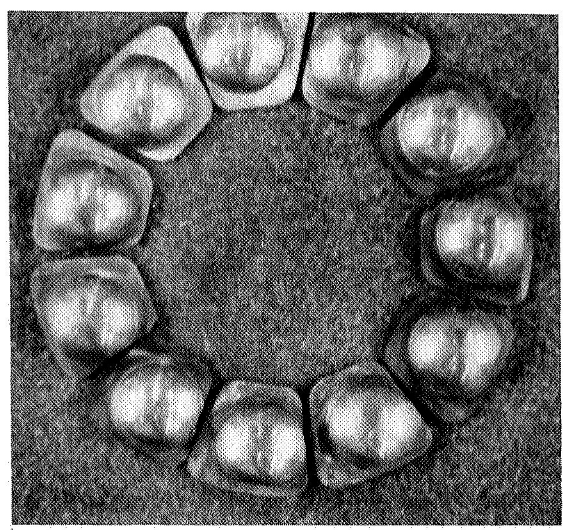
c. Swash Plate



d. Swash Plate

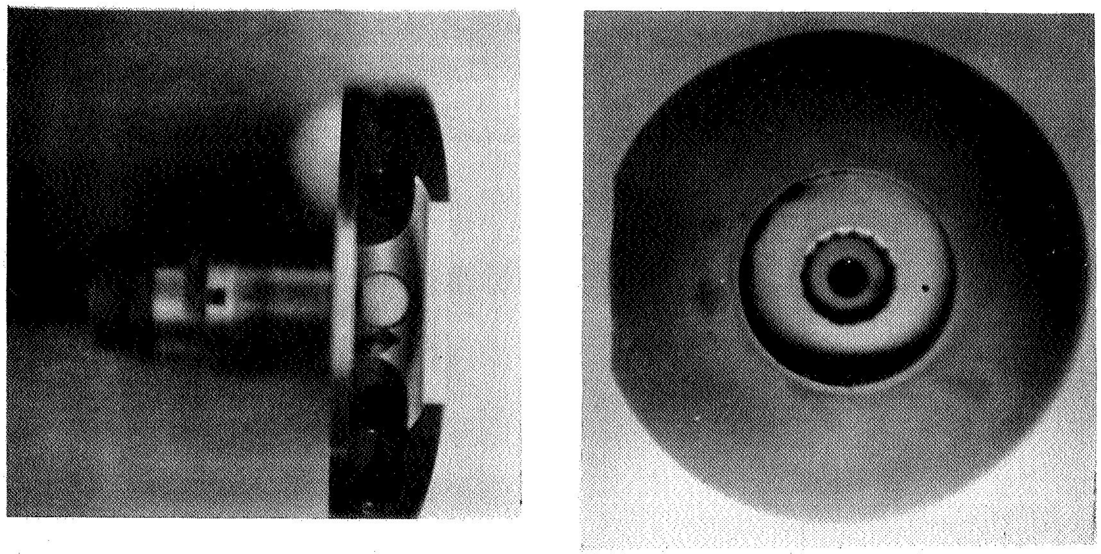


e. Thrust Bearings



f. Thrust Bearings

Figure 14. K-82 Shoes and Thrust Bearings and K-96 Swash Plate As Received in Pump S/N X-1800



a. Side View

b. Front View

Figure 15. Balanced K-96 (Tungsten Carbide + 6% Cobalt) Swash Plate

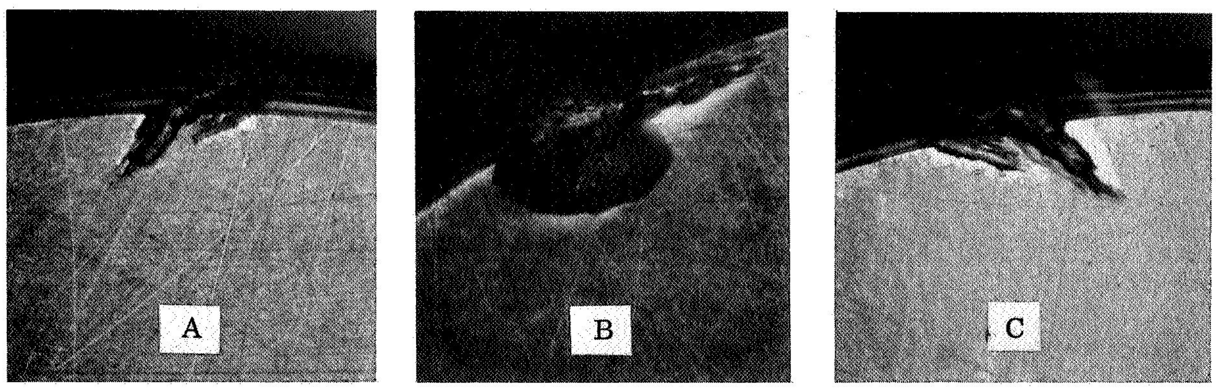


Figure 16. Damaged Edges of K-82 Shoe No. 3
After Break-In Test (Magnification: 20X)

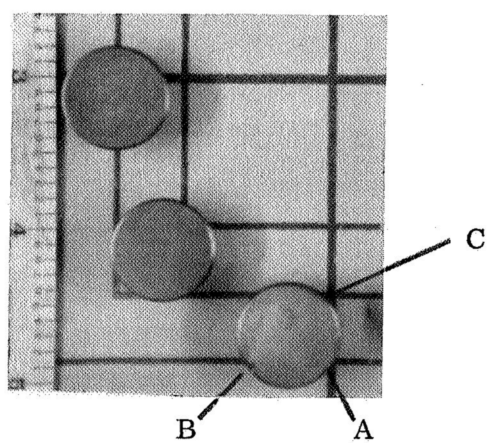


Figure 17. K-82 Shoe No. 3 After Edges Were Smoothed

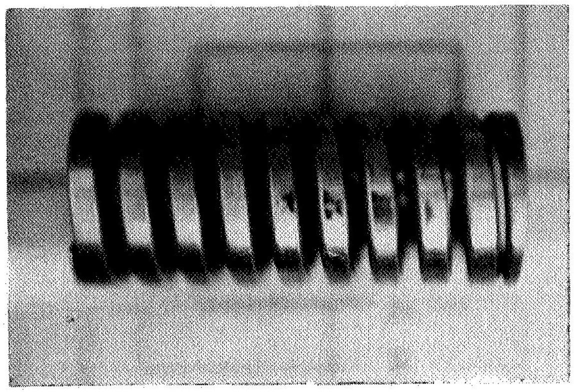


Figure 18. Outer Compensator Spring

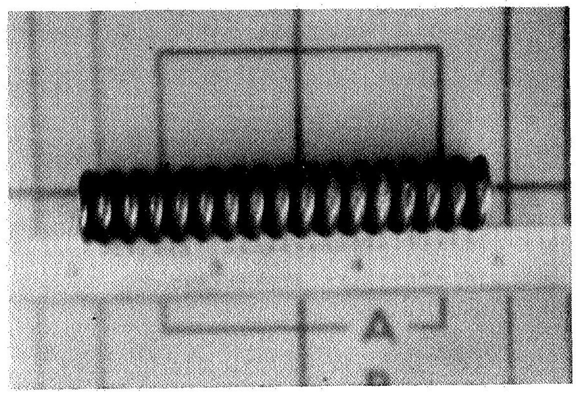


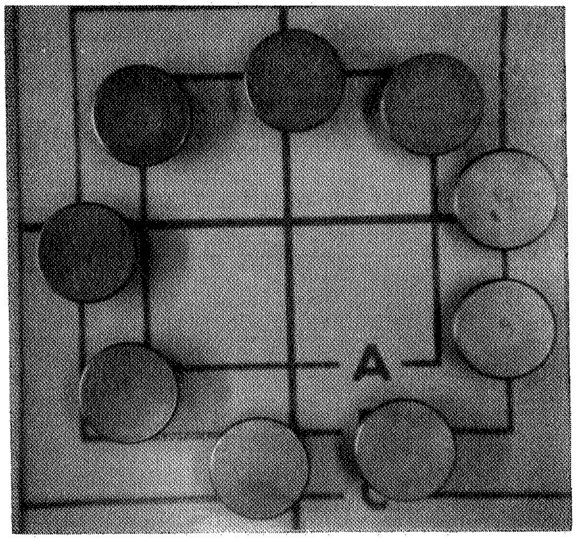
Figure 19. Inner Compensator Spring

suspected as the cause of filter clogging. Both line and filter elements as well as the two static O-ring shaft seals were replaced before the test continued. The test was stopped a third time after 37 hours to replace the line filter element which had a 400 psi drop at 7.6 gpm. The shaft seal leakage during this interval was less than 0.5 ml. During the third interruption the pressure line filter element (rated at 10-micron nominal) was removed and found to be clogged with metallic particles. A clean filter element was installed in the system. While the system was down the pump was also disassembled and the internal parts inspected. There were no visible signs of pump damage. The test was continued until 50 hours was logged. The shaft seal leakage during the last 13 hours of the test was less than 1 ml.

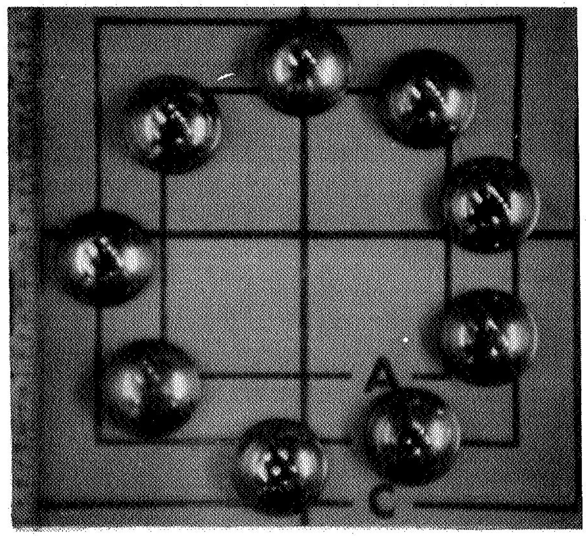
After the test the critical pump parts were found to be in excellent condition, Figure 22. The weights and height changes of the shoes and bearings were again negligible, Table IV. Minor changes in the viscosity and acid number of the mineral oil were noted, Figure 21. The fluid and the components in the system appeared in good condition after the 500°F test.

3. <u>550°F Test</u>

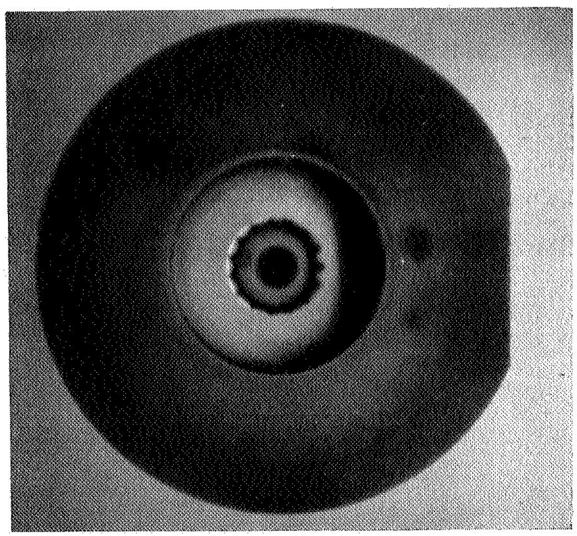
It was decided to introduce a 25-hour test at 550°F before attempting a 600°F test. Filter elements rated at 17- and 5-micron nominal were installed



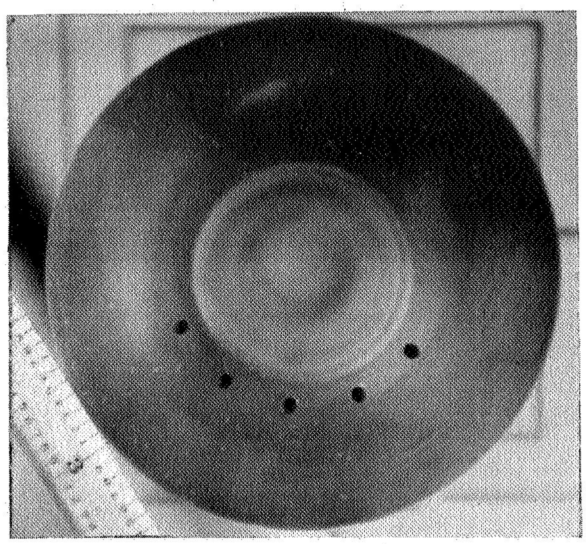
a. Shoes



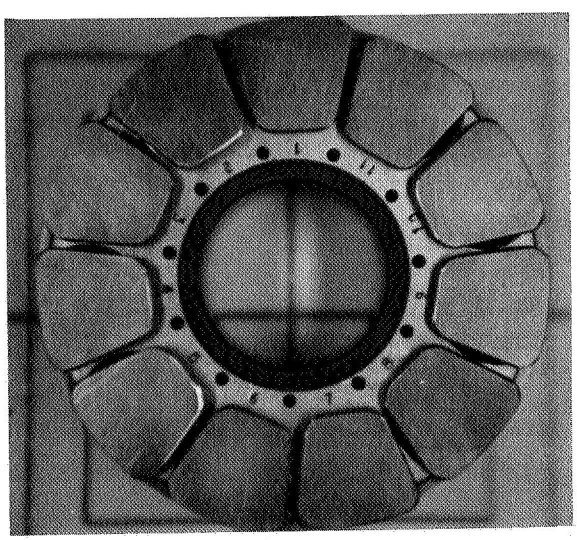
b. Shoes



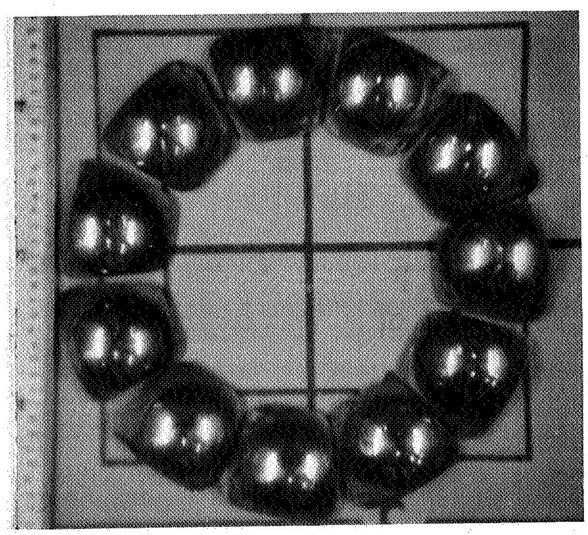
c. Swash Plate



d. Swash Plate



e. Thrust Bearings



f. Thrust Bearings

Figure 20. K-82 Shoes and Thrust Bearings and K-96 Swash Plate After 50 Hours at 400°F With MLO 60-294 Mineral Oil

TABLE IV - DIMENSIONAL AND WEIGHT CHANGE OF K-82 SHOES AND THRUST BEARINGS (PUMP S/N X-1800)

	Weight Change (Grams)				Dimensional Change (Inches)			
Shoe No.	As Received	50 Hours @ 400°F	50 Hours @ 500°F	21.5 Hours @ 600°F	As Received	50 Hours @ 400°F	50 Hours @ 500°F	21.5 Hours @ 600°F
1	11.0165	11.0162	11.0163	11.0161	.2502	.2502	.2502	.2505
2	10.9644	10.9621	10.9614	10.9598	.2506	.2505	.2504	.2503
3	10.8788	10.8743*	10.8741	10.8726	.2505	.2504	.2503	.2501
4	10.9829	10.9827	10.9827	10.9827	.2506	.2506	.2505	.2505
5	10.9436	10.9425	10.9412	10.9392	.2509	.2509	.2507	.2507
6	10.9365	10.9361	10.9355	10.9359	.2505	.2506	.2505	.2508
7	10.8527	10.8526	10.8523	10.8521	.2505	.2504	.2503	.2503
8	10.9753	10.9725	10.9720	10.9712	.2504	.2504	.2503	.2502
9	10.8902	10.8902	10.8902	10.8894	.2504	.2505	.2503	.2502
Bearing No.								
1	17.7427	17.7425	17.7426	17.7430	.3159	.3158	.3158	.3158
2	17.7255	17.7253	17.7254	17.7248	.3168	.3156	.3156	.3156
3	17.8162	17.8160	17.8163	17.8176	.3157	.3157	.3157	.3157
4	17.8628	17.8629	17.8624	17.8625	.3158	.3158	.3157	.3158
5	17.9458	17.9458	17.9458	17.9460	.3157	.3157	.3157	.3157
6	17.7549	17.7544	17.7544	17.7548	.3156	.3155	.3155	.3156
7	17.7805	17.7803	17.7805	17.7812	.3156	.3156	.3156	.3156
8	17.7773	17.7769	17.7764	17.7772	.3156	.3156	.3156	.3156
9	17.7671	17.7665	17.7665	17.7665	.3158	.3158	.3158	.3158
10	17.8260	17.8262	17.8262	17.8274	.3157	.3157	.3157	.3157
11	17.6560	17.6556	17.6555	17.6555	.3157	.3157	.3156	.3157

in the case drain and pressure lines, respectively. The mineral oil was pumped in the system for a total of 22.8 hours at 550°F inlet pump temperature. At 7.9 hours the pressure drop across the 5-micron filter was about 500 psi. A few metal particles were observed in the filter element convolutes and in the filter bowl. It is believed, though, that fluid lacquering and/or additive removal were mostly responsible for the high pressure drop across the element. Extracts from the filter element were sent to the fluid vendor for analysis. The pressure drop across the case drain, 17-micron filter element was 2 psi. Both filters were replaced with 10-micron elements before the test was restarted.

At 8.4 hours the low flow rate was increased from 3 to 5 gpm when the high pitch pump noise, associated with the low flow rate, was abated. The test was terminated at 22.8 hours because of a 500 psi drop across the pressure line filter. Again, fluid lacquering and/or additive decomposition are believed responsible for the high pressure differential. Shaft seal leakage was negligible throughout the test.

Fluid samples were taken from the system at 5, 10, 20, and 22.8 hours. Viscosity and acid number measurements are plotted in Figure 21. The fluid changed in color from a medium yellow to amber. Examination of the internal parts of the pump revealed no change. No measurements were made on the shoes and thrust bearings during this inspection.

4. 600°F Test

Prior to the test, 40-micron nominal elements were placed in the pressure and case drain line filters. The pump was run for a total of 21.5 hours at 600°F pump inlet temperature when one of the Viton O-rings failed causing excessive leakage. Toward the end of the test the pressure drops across the case drain and pressure line filters were 50 and 10 psi, respectively. The test was not continued as the goal of 25 hours was almost reached.

The fluid had a hazy, amber appearance. Slight shearing of the fluid occurred as indicated by viscosity measurements made on the 5, 10, 19, 5, and 21.5-hour fluid samples, Figure 21. The shoes and thrust bearings were in excellent condition, Figures 23a and 23b. Slight weight losses in the shoes were measured, Table IV. Some scratch marks were made on the swash plate which mates with the thrust bearings during this test, Figure 23c.

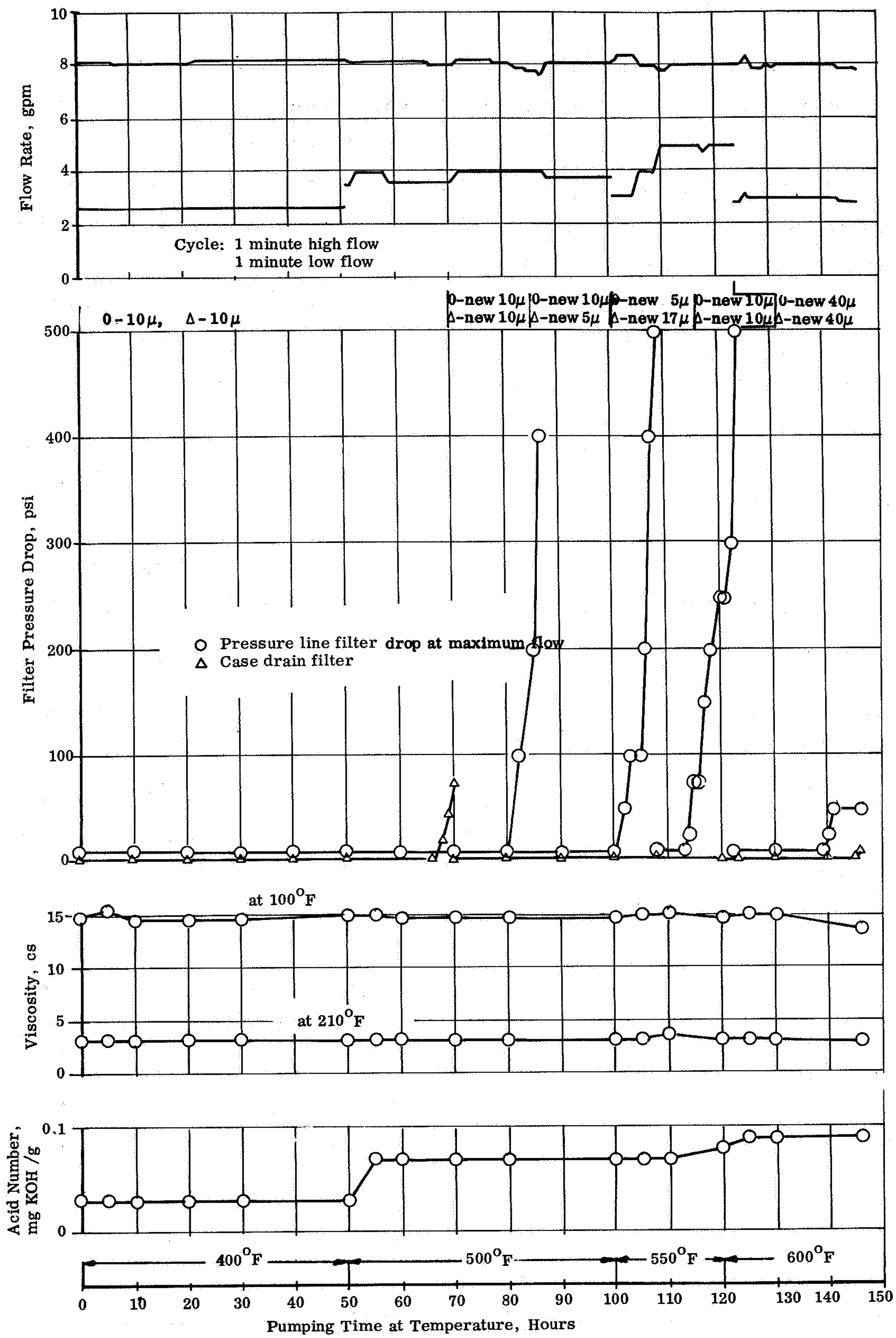
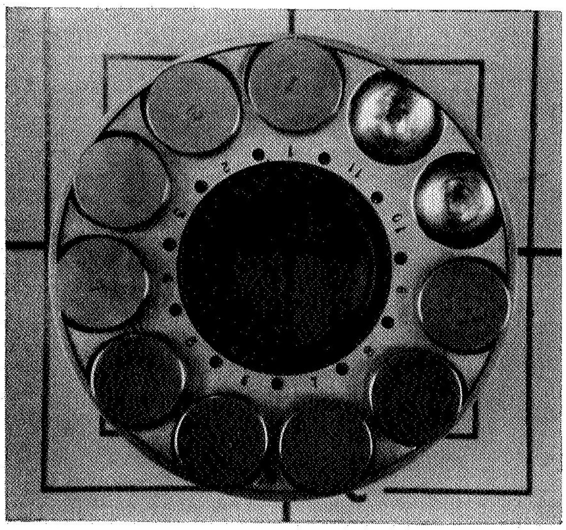
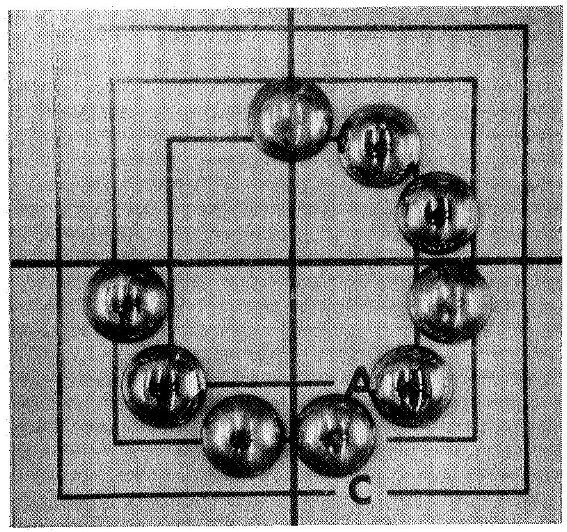


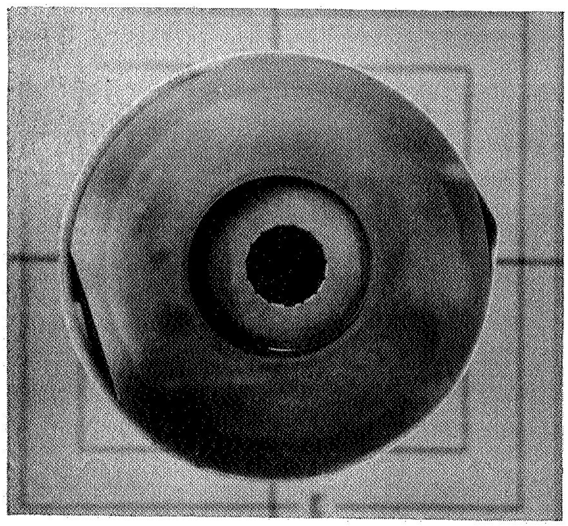
Figure 21. Flow Rate, Filter Pressure Drop, Viscosity, and Acid Number Change During Pump Tests with Deep-Dewaxed Superrefined Mineral Oil

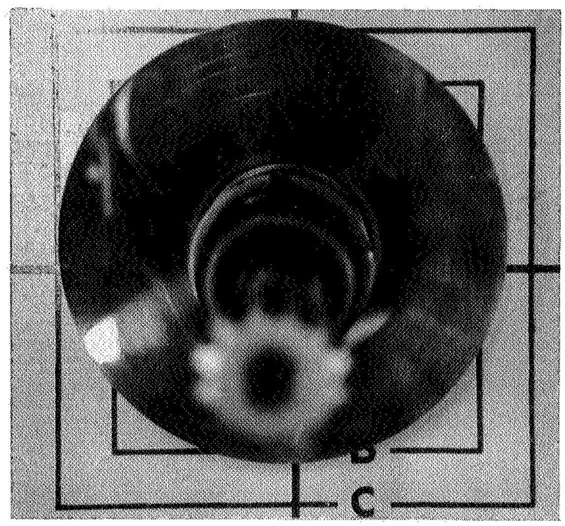




a. Shoes

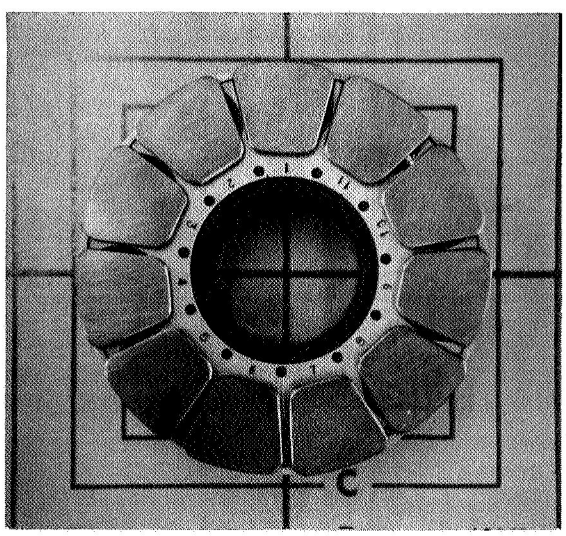
b. Shoes

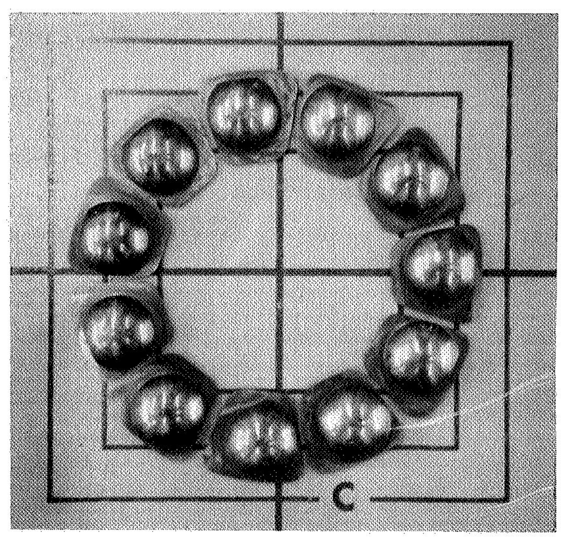




c. Swash Plate

d. Swash Plate

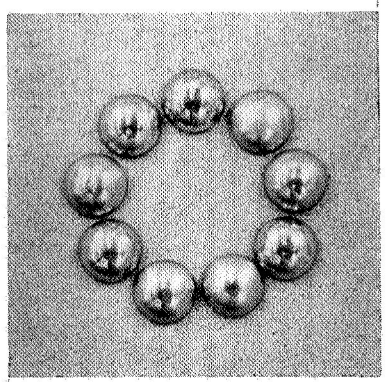




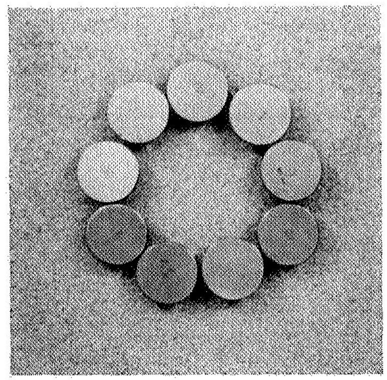
e. Thrust Bearings

f. Thrust Bearings

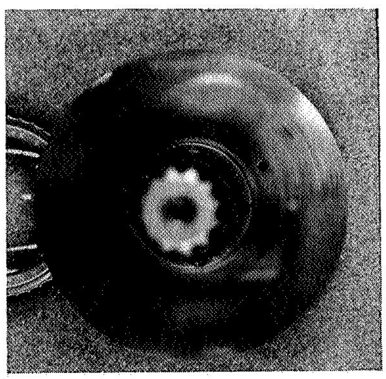
Figure 22. K-82 Shoes and Thrust Bearings and K-96 Swash Plate After 50 Hours at 500°F With MLO 60-294 Mineral Oil



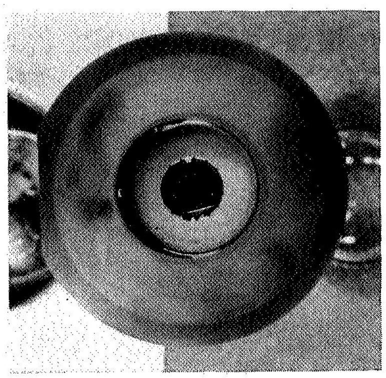
a. Shoes



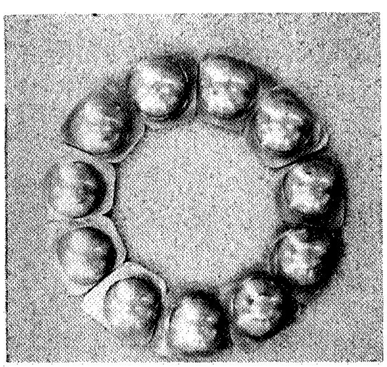
b. Shoes



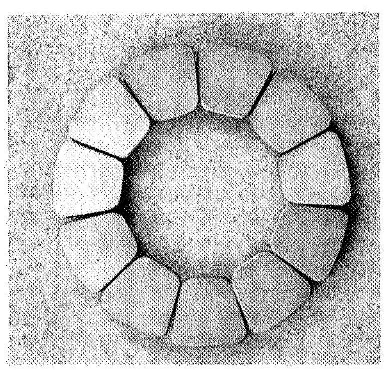
c. Swash Plate



d. Swash Plate



e. Thrust Bearings



f. Thrust Bearings

Figure 23. K-82 Shoes and Thrust Bearings and K-96 Swash Plate After 21.5 Hours at 600°F with MLO 60-294 Mineral Oil

D. PUMP TESTS WITH MCS-3104 HALOGENATED POLYARYL FLUID

MCS-3104 (polyaryl fluid with improved stability and wear additives) was pump-tested for 50 hours at 400°F and for 4.4 hours at 500°F when filter clogging occurred. The pump was broken-in by gradually increasing the pump pressure to 3000 psi in 500 psi increments and later increasing the temperature to 380°F with occasional cycling.

1. 400°F Test

Pump pressure was 3000 psi and the fluid was cycled from 3 to 8 gpm in one minute intervals at each flow rate. After 41 hours at 400°F the pressure differentials across the pressure line and case drain filters increased to 50 psi at 40 gpm and 80 psi, respectively. The case drain filter was replaced with a 17-micron at this time. The pressure drop across each of the latter elements was about 4 psi at the end of the test.

Examination of the 10-micron elements removed from the system after 41 hours indicated that additive and/or fluid decomposition may have caused the pressure differential rise. Samples of the fluid and extracts from the filter were sent to the fluid vendor for analysis. Viscosity and acid number determinations on the fluid samples recovered from the system (Figure 24) showed slight decrease in viscosity but a significant increase in acid number.

2. 500°F Test

After 50 hours at 400°F the pump inlet temperature of the fluid was raised to 500°F without interruption between tests. Upon reaching 500°F a gradual build-up of the pressure differential across the pressure line filter was observed. After 4.4 hours at 500°F the pressure line filter pressure differential was 275 psi at 6.6 gpm and the case drainfilter pressure drop was 6 psi.

The test was stopped at the 4.4-hour point. Removal and inspection of the filter elements revealed a dark brown coating on each element. This condition prompted examination of the pump when it was discovered that a dark brown viscous material was formed around the moving parts in the pump. The

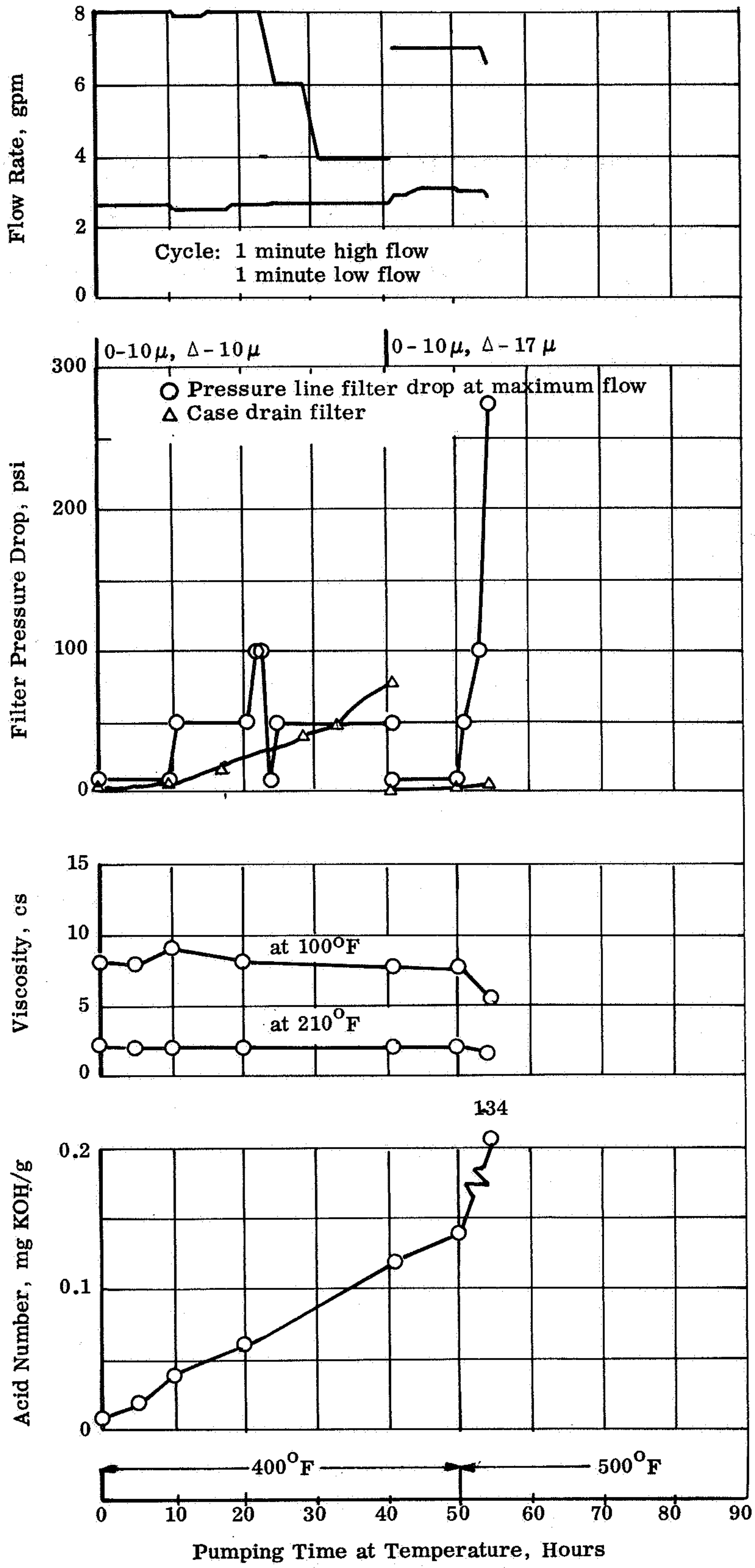


Figure 24. Flow Rate, Filter Pressure Drop, Viscosity and Acid Number Change During Pump Tests with Halogenated Polyaryl Fluid

shoes and pistons were frozen in the piston sockets and cylinder barrel, respectively. The shoes, thrust bearings and swash plate were not damaged but the pistons and cylinder barrel were unsalvageable. Shoe and thrust bearing weight and height changes were negligible as indicated in Table V.

Fluid and/or additive degradation after 4.4 hours at 500°F appreciably affected viscosity, 5.63 cs at 100°F and 1.79 cs at 210°F, and acid number, 1.34 mg KOH/g, Figure 24.

E. PUMP TESTS WITH PR-143AB FLUOROCARBON FLUID

The pump (containing Star J shoes and thrust bearings and a 440C + 4% molybdenum swash plate) originally scheduled for testing with the fluorocarbon fluid was replaced with an available pump containing the K-82/K-96 bearing material combination. Boundary lubrication tests had earlier shown that the carbide materials were effectively lubricated by PR-143AB fluid.

1. 400°F Test

The fluorocarbon fluid was pump-tested for 50 hours at 400°F without interruption. The pressure drop across each of the two 10-micron filters was less than 2 psi at the conclusion of the test. The appearance of the recovered fluid samples was milky white. Viscosity and acid number changes of the fluid during the run were negligible, Figure 25. A greenish-blue rainbow hue was observed on the piston and cylinder barrel surfaces. This surface film did not affect the pump operation.

2. 500°F Test

Clean 10-micron filter elements were installed in the system prior to the 500°F test. The 50-hour test was interrupted once at 36.5 hours because of pump shaft seal leakage. The pressure drop across each filter element was less than 2 psi at the end of the test. Viscosity and acid number of the fluid did not change significantly during the test, Figure 25. The pump appeared in good condition. No measurements were taken on the shoes or bearings.

3. 600°F Test

The filter elements from the preceding run remained in the system. The test was conducted for a total of 37.3 hours at 600°F. Three interruptions

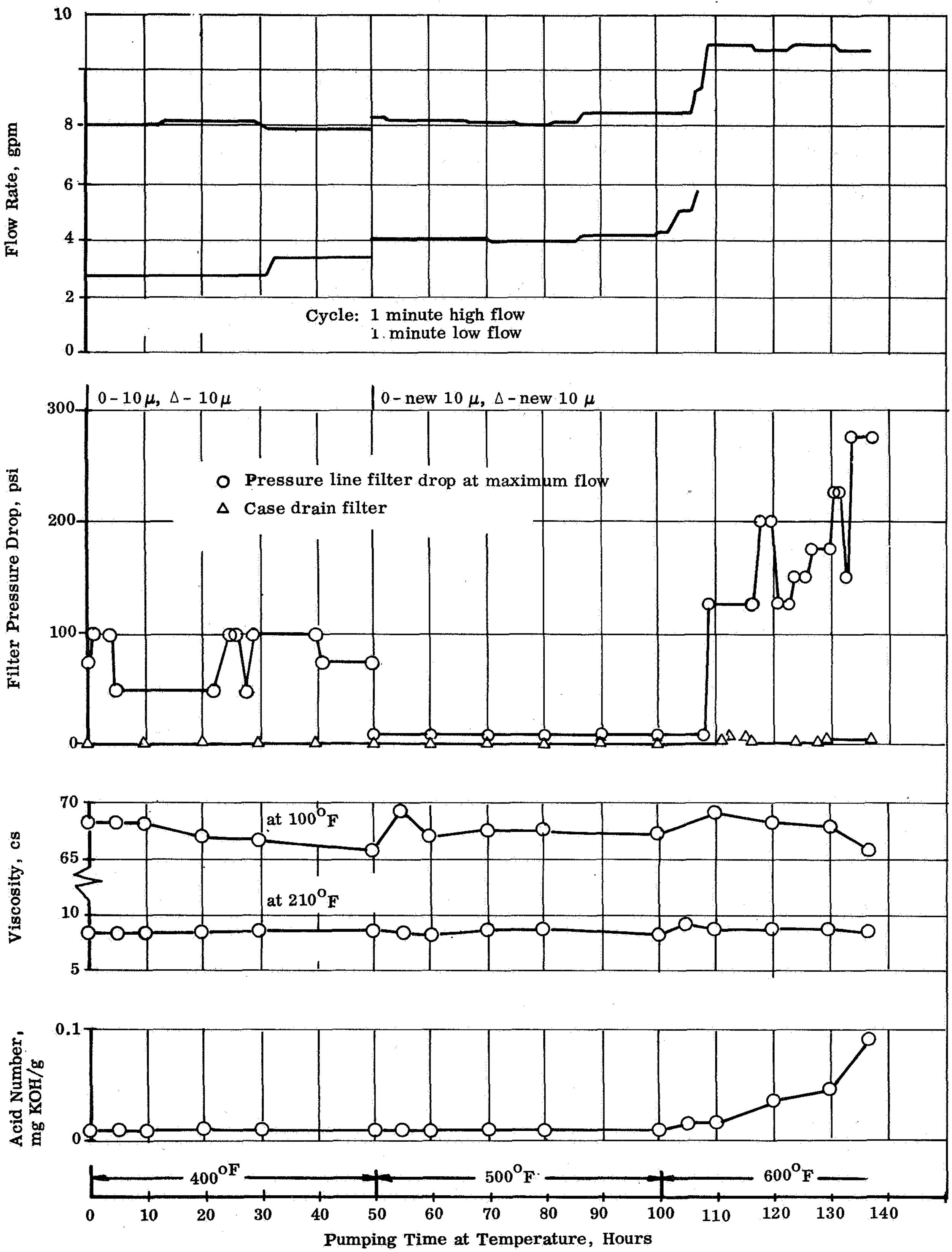


Figure 25. Flow, Filter Pressure Drop, Viscosity and Acid Number Change During Pump Tests with Fluorocarbon Fluid

occurred during the test because of pump shaft seal leakage. Small but significant changes were detected in viscosity (5% decrease) and acid number (0.074 mg KOH/g increase) during the 37.3 hour run, Figure 25. Weight and height measurements of the shoes and thrust bearings before the break-in and after the 600°F test showed slight weight losses in shoes and bearings, Table V.

F. SUMMARY OF PUMP TEST EVALUATIONS ON FLUIDS

The results of the pump loop tests are summarized in Table VI. Additional information on earlier pump tests under similar test conditions is included in Table VII.

There was little difficulty in pumping F-50 silicone oil for 50 hours at 400°F. It would appear that the bronze-on-tool steel is an ideal bearing material combination for the silicone oil. However, upon closer examination it was found that the presence of any zinc in Pheldor 10 and in Mueller 600 (Ref. 5) was chemically removed by the fluid at 400°F. A deterioration of the properties of the bronze shoes and thrust bearing may have occurred in proportion to the zinc content. Negligible change in fluid properties was detected during pump operation at 400°F.

After a few hours at 500°F, seizure of the bronze-on-tool steel occurred in several pump tests. This seizure is thought to be induced by an alteration of the oxide surface of the tool steel swash plate. With a depletion or alteration in swash plate surface oxide coating the bronze ultimately transfers and thereby leads to seizure. Oxygen starved conditions caused by degassing the fluid and inerting the system may have hastened the process.

The pumpability of F-50 silicone oil appears to be limited by the bearing material combination employed. Besides the chemical interaction of the fluid on the bearing materials the hot hardness of the bronze decreases appreciably at 500°F, (Ref. 6). The impact of the pistons was high enough to deform the bronze shoes, in this particular pump. Fluid shearing was indicated by the viscosity change. The acid content of the fluid also increased during the 500°F test runs.

TABLE V - WEIGHT AND HEIGHT MEASUREMENTS OF K-82 SHOES AND THRUST BEARINGS DURING PUMP TESTS WITH MCS-3104 FLUID (PUMP S/N X-1801)

	Before Break-in Test		After 4.4 Hrs @ 500°F	
Shoe No.	Weight, g	Height, in.	Weight Change, g	Height Change, in.
1	10.7854	.2500	-.0044	0
2	10.7835	.2492	-.0035	0
3	10.7913	.2479	-.0039	-.0001
4	10.7785	.2492	-.0039	0
5	10.7787	.2509	-.0042	0
6	10.8060	.2480	-.0039	0
7	10.8298	.2492	-.0038	0
8	10.7177	.2490	-.0039	0
9	10.8072	.2495	-.0048	-.0003
Bearing No.				
1	17.5955	.3158	-.0031	0
2	17.6647	.3157	-.0035	0
3	18.0625	.3158	-.0019	0
4	17.6439	.3158	-.0031	0
5	17.7784	.3158	-.0033	0
6	17.6301	.3158	-.0033	0
7	17.8558	.3156	-.0031	0
8	17.7566	.3159	-.0033	-.0001
9	17.6523	.3159	-.0007	0
10	17.7212	.3159	-.0039	0
11	17.6555	.3155	-.0024	0

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS

Test No. 1 - Break-in Test		Remarks
Pump S/N	1803	Pressure was increased to 3000 psi in 500 psi increments. Pump hunted excessively below 4 gpm. No pump shaft seal leakage.
Fluid	F-50	
Maximum Temperature (°F)	400	
Time @ Temperature (hr)	-	
Time, Total Run (hr)	3.25	
Shoes and Bearings	Pheldor-10	
Swash Plate	M-2	
Flow (gpm)	2.5 to 12	
Pump End Clearance (mils)	10.5	
Test No. 2 - 400°F Test		
Pump S/N	1803	Cycled at 2 minute intervals. Shaft seal started to leak after 2.66 hr. @ 400°F. Leakage at 18 hrs. was 38 drops per minute. Replaced static Viton O-ring shaft seal at 18 hrs. At 25 hr. mark pressure across pressure line filter was 400 psi. Shaft seal leakage was 1 dpm. Replaced line filter element after 25 hours. Shaft seal started to leak at 27 hr. mark. Slight hunting during cycling. At end of run shaft seal leakage was 60 dpm.
Fluid	F-50	
Maximum Temperature (°F)	400	
Time @ Temperature (hr)	50	
Time, Total Run (hr)	50.35	
Shoes and Bearings	Pheldor-10	
Swash Plate	M-2	
Flow (gpm)	4 to 9	
Pump End Clearance (mils)	10.5	
Test No. 3 - 500°F Test		
Pump S/N	1803	No cycling because of excessive pump hunting. Shaft seal leakage was 6 dpm at 2 hr. mark. Leakage remained constant till end of test. Total seal leakage was 30 cc. Neck of cylinder block broke upon disassembly.
Fluid	F-50	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	5	
Time, Total run (hr)	6.1	
Shoes and Bearings	Pheldor-10	
Swash Plate	M-2	
Flow (gpm)	8.6	
Pump End Clearance (mils)	10.5	

General Notes

Reservoir pressure: 50 to 70 psi
Pump speed: 3600 rpm
Flow cycle: 1 minute high flow, 1 minute low flow
Filter element - 10 micron nominal (unless otherwise indicated)

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS (Continued)

Test No. 4 - Break-in Test		Remarks
Pump S/N	1803A	Replaced cylinder block, pistons and spool valve before the test. Used same bearings and swash plate as in preceding test.
Fluid	F-50	
Maximum Temperature (°F)	RT-225	
Time @ Temperature (hr)	-	
Time, Total run (hr)	.83	
Shoes and Bearings	Pheldor-10	
Swash Plate	M-2	
Flow (gpm)	2.5 - 8.7	
Pump End Clearance (mils)	11	
Test No. 5 - Break-in Test		
Pump S/N	1802	Increased pressure to 3000 psi in 500 psi increments. Shut down system when torquemeter needle indicator started to flicker.
Fluid	MCS-293	
Maximum Temperature (°F)	RT-350	
Time @ Temperature (hr)	-	
Time, Total run (hr)	1.9	
Shoes and Bearings	S Monel	
Swash Plate	M-2	
Flow (gpm)	2 - 12	
Pump End Clearance (mils)	9	
Test No. 6 - Break-in Test		
Pump S/N	1800	Excessive pump vibration due to unbalanced swash plate.
Fluid	MLO 60-294	
Maximum Temperature (°F)	RT	
Time @ Temperature (hr)	-	
Time, Total run (hr)	.01	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	-	
Pump End Clearance (mils)	9	
Test No. 7 - 500°F Test		
Pump S/N	1803A	No shaft seal leakage. Pump spline shaft sheared.
Fluid	F-50	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	.08	
Time, Total run (hr)	1.41	
Shoes and Bearings	Pheldor-10	
Swash Plate	M-2	
Flow (gpm)	2.5-8.5	
Pump End Clearance (mils)	11	

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS (Continued)

Test No. 8 - 500°F Test		Remarks
Pump S/N	1803A	No shaft seal leakage. Pump spline shaft sheared.
Fluid	F-50	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	2	
Time, Total run (hr)	2.73	
Shoes and Bearings	Pheldor 10	
Swash Plate	M-2	
Flow (gpm)	2.5 - 8.2	
Pump End Clearance (mils)	10.5	
Test No. 9 - Break-in Test		
Pump S/N	1800	No shaft seal leakage. Leak in flange inlet to pump. Shoe No. 3 chipped in three places.
Fluid	MLO 60-294	
Maximum Temperature (°F)	RT-380	
Time @ Temperature (hr)	-	
Time, Total run (hr)	3.4	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	2.5 - 12.5	
Pump End Clearance (mils)	8.5	
Test No. 10 - 400°F Test		
Pump S/N	1800	Total shaft seal leakage was 1 cc.
Fluid	MLO 60-294	
Maximum Temperature (°F)	400	
Time @ Temperature (hr)	50	
Time, Total run (hr)	50.8	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	2.7 - 8.2	
Pump End Clearance (mils)	8.5	
Test No. 11 - 500°F Test		
Pump S/N	1800	Shut down system at 7.4 hr. mark because of leaks in weld and braze lines. Shaft seal leakage was 1 cc. Repaired lines and changed shaft seal O-rings. Shut down system at 20 hr. mark. Case drain filter (10 micron) pressure drop rose to 75 psi. Replaced case drain and line filter elements.
Fluid	MLO 60-294	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	50	
Time, Total run (hr)	52.5	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	3.5 - 8.2	
Pump End Clearance (mils)	8.5	

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS (Continued)

Test No. 11 - 500°F Test (continued)		Remarks
Pump S/N	1800	Both static O-rings in shaft seal were replaced at 20-hour mark. At 37 hours line filter element (10-micron) pressure drop was 400 psi. Installed 10-micron and 5-micron elements in line and case drain filters, respectively. Replaced both static O-rings in shaft seal. At end of run line and case drain filter pressure drops were 10 and 2 psi, respectively. Total shaft seal leakage during 50-hour run was less than 2 ml.
Fluid	MLO 60-294	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	50	
Time, Total run (hr)	52.5	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	2.6 - 8.2	
Pump End Clearance (mils)	8.5	
Test No. 12 - 550°F Test		
Pump S/N	1800	Replaced pressure line filter with 5-micron element and case drain filter with 17-micron element. At 4.6 hours flow cycle changed to 4 and 8 gpm because of pump noise at low flow. At 7.9 hours the line filter pressure drop was about 500 psi. Few metal particles were observed on 5-micron element. Pressure drop was 2 psi across case drain filter. Both filter elements were replaced with 10-micron nominal. Both O-ring static seals in pump were replaced. Shaft seal leakage was negligible. Line pressure gage was replaced because it became erratic. At 8.4 hrs flow cycle was adjusted to 5 and 8 gpm because of pump noise. At 22.8 hours test was terminated because of 500 psi drop across line filter. Filter clogging is believed to be due to sludging of fluid. Case drain filter pressure drop was 15 psi. Shaft seal leakage was negligible throughout test.
Fluid	MLO 60-294	
Maximum Temperature (°F)	550	
Time @ Temperature (hr)	22.8	
Time, Total Run (hr)	24.4	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	3-8	
Pump End Clearance (mil)	8.5	

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS (Continued)

Test No. 13 - 600°F Test		Remarks
Pump S/N	1800	Line and case drain filters were installed with 40-micron nominal elements. Pressure drop across line and case drain filter elements at end of test were 50 and 10 psi, respectively. Test was terminated at 21.5 hours because excessive shaft seal leakage.
Fluid	MLO 60-294	
Maximum Temperature (°F)	600	
Time @ Temp (hr)	21.5	
Time, Total Run (hr)	22.8	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	3-8	
Pump End Clearance (mils)	8.5	
Test No. 14 Break-in Test		
Pump S/N	1801	Increased pressure to 3000 psi in 500 psi increments.
Fluid	MCS-3104	
Maximum Temperature (°F)	RT-380	
Time @ Temperature (hr)	-	
Time, Total Run (hr)	1.5	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	12	
Pump End (Clearance (mils)	10	
Test No. 15 Break-in Test		
Pump S/N	1800	Increased pressure to 3000 psi in 500 psi increments.
Fluid	PR-143AB	
Maximum Temperature (°F)	RT-400	
Time @ Temperature (hr)	-	
Time, Total Run (hr)	1.4	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	12	
Pump End Clearance (mils)	8.5	
Test No. 16 - 400°F Test		
Pump S/N	1800	Line and case drain filters were installed with 10-micron elements. Pressure drop across pressure line filter was 75 psi and across case drain filter was 2 psi at end of test.
Fluid	PR-143AB	
Maximum Temperature (°F)	400	
Time @ Temperature (hr)	50	
Time, Total Run (hr)	51.8	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	3-8	
Pump End Clearance (mils)	8.5	

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS (Continued)

Test No. 17 - 400°F Test		Remarks
Pump S/N	1801	10-Micron elements were installed in line and case drain filters. Pressure drop across case drain filter was 80 psi and across pressure line filter was 275 psi at 41 hours. Both filters were replaced with 17-micron elements. Pressure drops of line filter (at 7 gpm) and of case drain filter were 10 psi and 2 psi at end of 50-hour run.
Fluid	MCS-3104	
Maximum Temperature (°F)	400	
Time @ Temperature (hr)	50	
Time, Total Run (hr)	51.8	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	3-8	
Pump End Clearance (mils)	10	
Test No. 18 - 500°F Test		
Pump S/N	1800	Replaced pressure line and case drain filters with clean 10-micron elements. Pressure drop across each filter was less than 10 psi at end of test. Test stopped at 36.5 hrs because of excessive pump shaft seal leakage (340 ml). Pressure drop of line filter was 25 psi and of case drain filter was 1 psi at end of run.
Fluid	PR-143AB	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	50	
Time, Total Run (hr)	51.5	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	4-8.1	
Pump End Clearance (mils)	8.5	
Test No. 19 - 500°F Test		
Pump S/N	1801	After 50 hours at 400°F (PT-17) the fluid temperature was raised to 500°F without shutdown between tests. Upon reaching 500°F the pressure drops of the 17-micron filters in the pressure and case drain lines were 75 psi and 7 psi, respectively. After 4.4 hours the pressure drop of the pressure line filter increased to 275 psi while the case drain filter pressure differential remained the same. The test was stopped for filter and pump examination.
Fluid	MCS-3104	
Maximum Temperature (°F)	500	
Time @ Temperature (hr)	4.4	
Time, Total Run (hr)	4.9	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	3-7	
Pump End Clearance (mils)	10	

TABLE VI - SUMMARY OF RECENT SIMPLE PUMP-LOOP TESTS (Continued)

Test No. 20 - 600°F Test		Remarks
Pump S/N	1800	Ten-micron filters from 500°F test (PT-18) remained in system. New elastomeric seals installed in pump prior to startup. The test was interrupted at 2.2, 31.6, and 37.3 hrs because of excessive pump shaft seal leakage. Pressure drops of pressure and case drain line filters were 275 and 3 psi, respectively, during constant flow of 10.6 gpm at 37.3 hours. Switched from cyclic to constant flow after 8 hours at temperature because of excessive hunting and pressure gage fluctuation at flows below 10 gpm. Line pressure remained at 3100 psi.
Fluid	PR-143AB	
Maximum Temperature (°F)	600	
Time @ Temperature (hr)	37.3	
Time, Total Run	39.3	
Shoes and Bearings	K-82	
Swash Plate	K-96	
Flow (gpm)	10.6	
Pump End Clearance (mils)	8.5	

TABLE VII - SUMMARY OF EARLIER PUMP-LOOP TESTS*

Fluid	Max. Temp. (°F)	Test Time	Pump	Remarks
Chlorinated Silicone	400 500	50 hrs. 8 hrs.	Standard 3600 RPM	Pump slippers seized
Deep-Dewaxed Mineral Oil	400	5 min.	Standard 3600 RPM	Pump main bearings failed
Synthetic Hydro-carbon	400 450	50 hrs.	Standard 3600 RPM	Pump slippers seized at 490°F during heat-up
High Viscosity Mineral Oil	400 450 500 550	50 hrs. 25 hrs. 50 hrs. 50 hrs.	Standard 3600 RPM	Completed run
Chlorinated Silicone	400 450 500	50 hrs. 20 hrs. 7 hrs.	Standard 3600 RPM	Pump slippers seized
Deep-Dewaxed Mineral Oil	400	2 hrs.	Standard 3600 RPM	Pump failed
Deep-Dewaxed Mineral Oil	550	121.2 hrs	Standard 3600 RPM	Main bearings failed, shaft sheared
Chlorofluoro Silicone	500	86 hrs.	Standard 3600 RPM	Slippers fused, shaft did not fail
High Viscosity Synthetic Hydrocarbon	450	62 hrs.	Standard 3600 RPM	Main bearing fused, shaft did not fail
High Viscosity Synthetic Hydrocarbon	500	72.5 hrs	Standard 3600 RPM	Slippers completely fused, shaft did not fail
Chlorinated Silicone	500	83.6 hrs	Standard 4500 RPM	Slippers fused, shaft and main bearings did not fail

* References: RTD-TDR-63-4078, Part I, Research on High Temperature Hydraulic Fluids for Supersonic Transport Aircraft, December 1963.
ML-TDR-64-323, High Temperature Hydraulic Fluids for Supersonic Transport Aircraft, December 1964

TABLE VII - SUMMARY OF EARLIER PUMP-LOOP TESTS (continued)

Fluid	Max. Temp. (°F)	Test Time	Pump	Remarks
Chlorinated Silicone	550	123 hrs.	High Speed 5800 RPM	Slippers damaged, main bearings slightly damaged, shaft not sheared
Polysiloxane	400	16 hrs.	Standard 3600 RPM	Slippers severely damaged, shaft sheared
Chlorinated Silicone	500	74.5 hrs.	High Speed	Slippers fused, shaft and main bearing not damaged
Deep-Dewaxed Mineral Oil	500	75 hrs.	Standard 3600 RPM	Main bearings failed
Polysiloxane	400	6 hrs.	Standard 3600 RPM	Slippers failed, shaft and main bearings not damaged, collar broken
Polysiloxane	400	10 hrs.	Standard 3600 RPM	Slippers failed, shaft and main bearings not damaged
Deep-Dewaxed Mineral Oil	500	114 hrs.	High Speed 5800 RPM	Slippers failed
Chlorinated Silicone	500	120 hrs.	Silver Slippers Std.-3600 RPM	One Shoe pounded, did not continue run
Polyphenyl Ether + T. C. P.	500	108 hrs.	Standard 3600 RPM	Back bearings smeared, compensator stuck
Chlorofluoro Silicone	500	85.5 hrs.	Standard 3600 RPM	Slippers smeared, back bearings good, shaft sheared
Deep-Dewaxed Mineral Oil	400-480	183 hrs.	Standard 3600 RPM	Bronze bearings failed
Chlorinated Silicone	400-480	416 hrs.	Standard 3600 RPM	-

GENERAL NOTES:

Operating Pressure 2850-3150 psig
Reservoir Pressure 30-50 psig

Flow: 0.5 gpm to 9.0 gpm in standard pump
2.0 gpm to 9 gpm in high speed pump
Cycle: 1 minute high flow, 1 minute low flow

The fluid pumpability limitations are relevant to the particular pump design and operating conditions. For example, it is shown in Table VII that with increased pump speed from 3600 to 4500 to 5800 rpm that a corresponding increase in pumpability of the F-50 silicone anywhere from 8 to 84 to 123 hours may be obtained. From Table VII it is also shown that a change in shoe materials from bronze to silver had a beneficial effect. If F-50 silicone oil is to be further evaluated it is recommended that a bearing material combination, such as K-82 on K-96 be tried. The performance of the fluid with this material combination has been shown to be satisfactory as evaluated during early boundary lubrication tests. A further upgrading of the pumpability of silicone oil may be possible by the copolymerization of chloro and fluoro silicone, Table VII.

The pump test with MCS-293 modified polyphenyl ether showed impending failure during the break-in of the pump with S Monel thrust bearings smearing and scoring M-2 tool steel.

No property changes in MLO 60-294 mineral oil during the 400°F pump tests were evident. However, although the fluid was shear resistant at 500°F a slight but definite increase in acid number was measured. At 550°F there was perceptible further increase in acid number. The fluid remained shear resistant. Within a few hours the 5- and 10- micron elements became clogged due to additive and/or fluid sludging. At 600°F evidence of permanent fluid shear occurred with some loss in viscosity. A 50 psid buildup occurred across a 40-micron element within a period of 37 hours.

MCS-3104 hologenated polyaryl fluid was marginal in performance at 400°F because it tended to sludge the filters and form acid products. Fluid degradation was more noticeable shortly after reaching 500°F. It should be pointed out, however, that this fluid was tested beyond its intended limit. The fluid had been developed for a specific application where the maximum fluid bulk temperature is 350°F.

Permanent shear occurred in PR-143AB fluorocarbon fluid at 400°, 500°, and 600°F. A 100 psi across the pressure line filter developed shortly after the 400°F test began. This pressure differential may have been caused by trace organic contamination reacting with the fluorocarbon to form a white semisolid. The pressure buildup did not rise greater than 100 psid. When the filter elements were replaced with 10-micron elements before the 500°F test the pressure drop remained low. At 600°F, the acid number started to rise to a value below 0.1 mg KOH/g fluid. Probable fluid sludging caused the 10-micron element to rise to 275 psid.

G. RECOMMENDATIONS FOR MAXIMUM FLUID TEMPERATURES FOR ENDURANCE TEST

It is recommended that the two fluids which passed the 600°F pump tests, namely, the deep-dewaxed mineral oil and the fluorocarbon fluid, be endurance-tested at maximum pump inlet temperatures of 450° and 500°F, respectively. Supporting data for using the recommended temperatures over a protracted time period are based on experience obtained by Republic Aviation and by Midwest Research Institute, Table VIII.

A maximum pump inlet temperature limitation of 450°F was selected for MLO 60-294, as presently formulated, because of sludging tendencies at elevated temperatures. In view of the long-term 3000-hour requirement it is believed that prolonged exposure of the mineral oil to a higher bulk oil temperature would promote sludge build-up that would adversely affect operation of close-tolerance moving components and filters in a hydraulic system.

PR-143AB should be restricted to a bulk oil temperature of 500°F because of a definite increase in acid number at 600°F. There is also a greater tendency for the filters to clog at the higher temperature. The fluid appears to remain stable at when pumped at 500°F.

TABLE VIII - REPUBLIC AND MIDWEST RESEARCH PUMP TEST DATA ON MLO 60-294 AND PR-143 FLUIDS

MLO 60-294

A. Republic data obtained during Contract AF 33(657)-9616
(Reference: ML-TDR-64-323, High Temperature Hydraulic Fluids For Supersonic Transport Aircraft)

1) 400°F to 480°F - 220 hrs, 3600 rpm pump speed; -2.1% viscosity @ 100°F, <.1 acid number change, bronze bearings failed
2) 500°F - 75 hrs. 3600 rpm; - 1.2% viscosity @ 100°F, <.1 acid number change, bronze bearings failed
3) 500°F - 114 hrs, 5800 rpm; -3.5% viscosity @ 100°F, <.1 acid number change, bronze slippers failed
4) 550°F - 121.2 hrs, 3600 rpm; -3.2% viscosity @ 100°F, <.1 acid number change, bronze bearings failed

B. Republic data from Contract NAS 3-7263

1) 400°F - 50 hrs; no change in viscosity or acid number
2) 500°F - 50 hrs; no change in viscosity or acid number
3) 550°F - 22.8 hrs; no significant change in viscosity, 5-μ filter clogged after 14.9 hrs
4) 600°F - 21.5 hrs; -6.7% viscosity @ 100°F, incipient pressure drop across 40-μ filter after 21.5 hrs

C. Midwest Research Contract AF 33(616)-6854
(Reference: WADD TR 60-855, Pt. II, Lubrication Behavior and Chemical Degradation Characteristics of Experimental High Temperature Fluids and Lubricants)

1) High Temperature hydraulic pump rig

   a. 400°F - 50 hrs; no change in viscosity or acid number
   b. 500°F - 47 hrs; no change in viscosity or acid number
   c. 550°F - 42 hrs; no change in viscosity or acid number
   d. 600°F - 25 hrs; no significant change in viscosity or acid number

2) Manton-Gaulin pump rig

   a. 550°F - 100 hrs; viscosity and acid number remained constant, 31 lb. breakout force on lacquer indicator shows lacquering tendency, 65 psi Δp across 10-μ filter @ 2.5 gpm in 75 hours (cause unknown), no change in flash or fire points

   b. 700°F - 27 hrs; 25 psi Δacross 10-μ filter attributed to Graphitar seals in pump, 41.5 lb. break-out force shows lacquer tendency; drop in flash and fire points, 23% drop in viscosity @ 100°F, no change in acid number

TABLE VIII - REPUBLIC AND MIDWEST RESEARCH PUMP TEST DATA ON MLO 60-294 AND PR-143 FLUIDS (Continued)

PR-143
A. Republic data from Contract NAS 3-7263 on PR-143 AB 1) 400°F - 50 hrs; no change in viscosity or acid number 2) 500°F - 50 hrs; no change in viscosity or acid number 3) 600°F - 37.3 hrs; - 5.3% viscosity @ 100°F, no sludging tendency apparent, .07 acid number increase
B. Midwest Research data from Contract MRI - AF 33(615)-3484, on PR143AC (Reference: QPR #3, Effect of Extreme Conditions on the Behavior of Lubricants and Fluids) 1) 400°F - 1000 hrs, -3% viscosity drop @ 210°F, .009 acid number increase, white deposits formed around bronze material, filter clogs in 480 hours.

TASK IV - COMPLETE SYSTEM FLUID TESTS

A. ADDITIONAL COMPONENTS TO PUMP LOOP

The two simple pump rigs formerly used in Task III, were revised for the endurance tests with MLO 60-294 and PR-143AB fluids. An actuator, spool valve, hot spot simulator, and filters of various pore sizes were connected in parallel and added to the system, Figure 26. New tubing was installed in the system and rerouted for ease of maintenance and to accommodate the additional components.

Exploded and cross sectional views of the actuator are shown in Figures 27 and 28. The chrome-plated 440 C stainless steel shaft is supported in the 17-4 PH housing by graphite bearings. The actuator is sealed in two stages. The primary piston seal and the secondary V-seal are made of Vespel. *

Fluid flows through the actuator in each system at a constant flow of one gpm and at 3000 psi. The actuators receive MLO 60-294 fluid at 460°F and PR-143AB fluid at 510°F. The rod of each actuator is cycled by a vari-drive motor at 20 cpm with a stroke of ±0.5 inch.

The fluid film on the actuator rod exposed to high temperature and to the atmosphere may form oxidized and corrosive products. The presence of these reaction products may adversely affect the seal and actuator performance.

The spool valve is shown in exploded and cross sectional views in Figures 29 and 30. From the illustrations it is seen that the 316 stainless steel valve is sealed at both ends with nickel fellows. One gpm of fluid flows through the valve at 3000 psi and 600°F. Drain ports are provided to collect leakage past the lands of the spool. The stroke of the spool is ± 1/16 inch.

Lacquering tendency and corrosive reactions of the fluid on the functioning of the spool valve and actuator are monitored. The force necessary to actuate the spool valve will be measured continuously during the test.

*DuPont trademark for polyimide plastic.

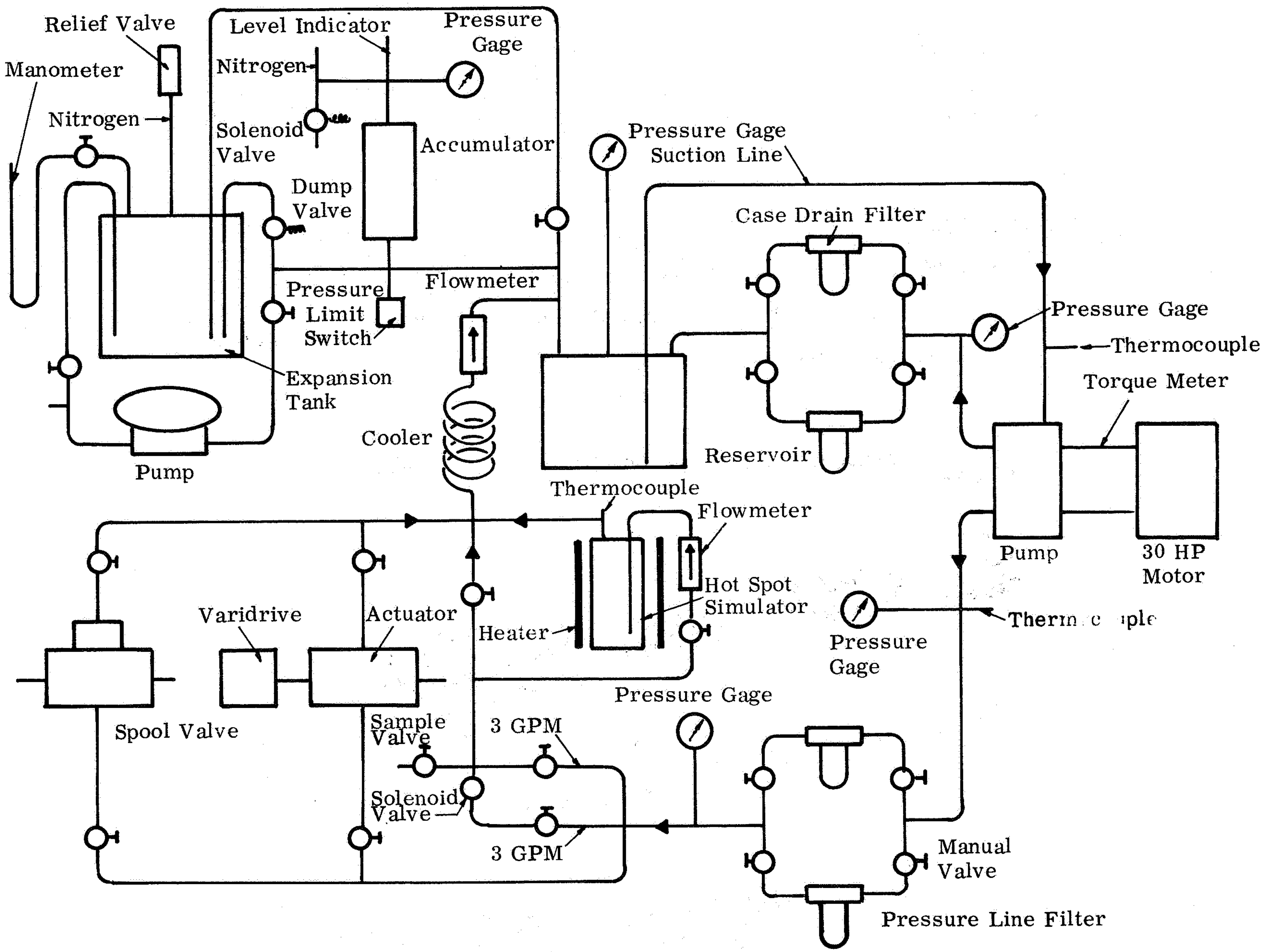


Figure 26. Schematic of Complete System Pump Rig

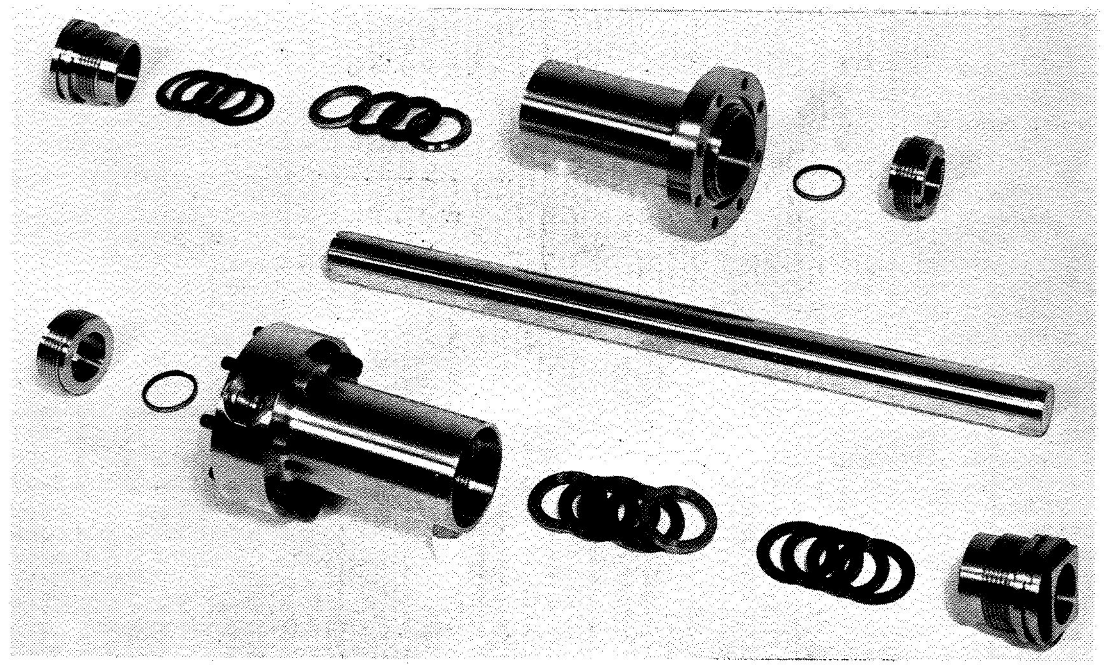


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Figure 27. Exploded View of Actuator Assembly

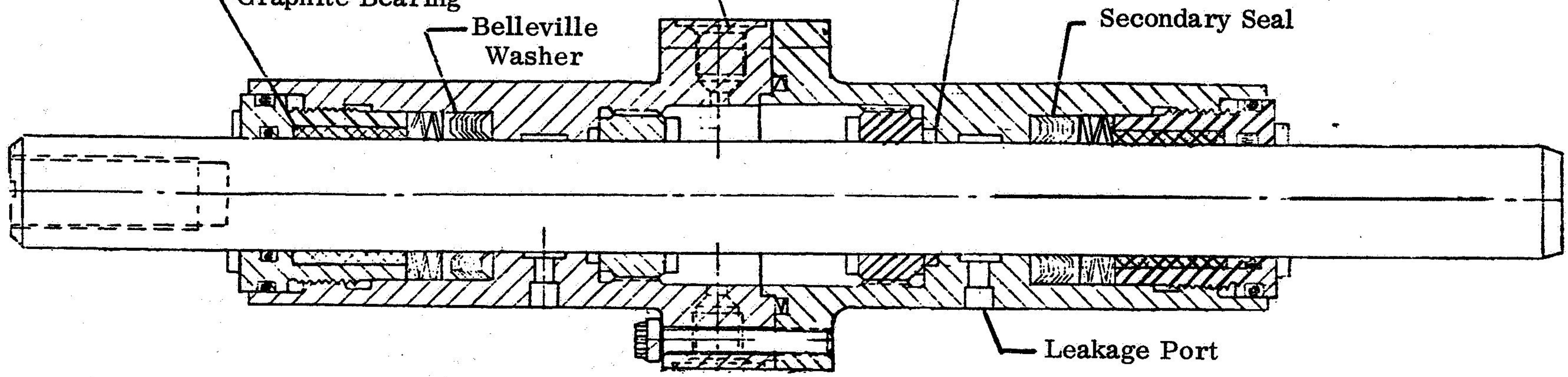

Figure 28. Cross Section of Actuator Assembly

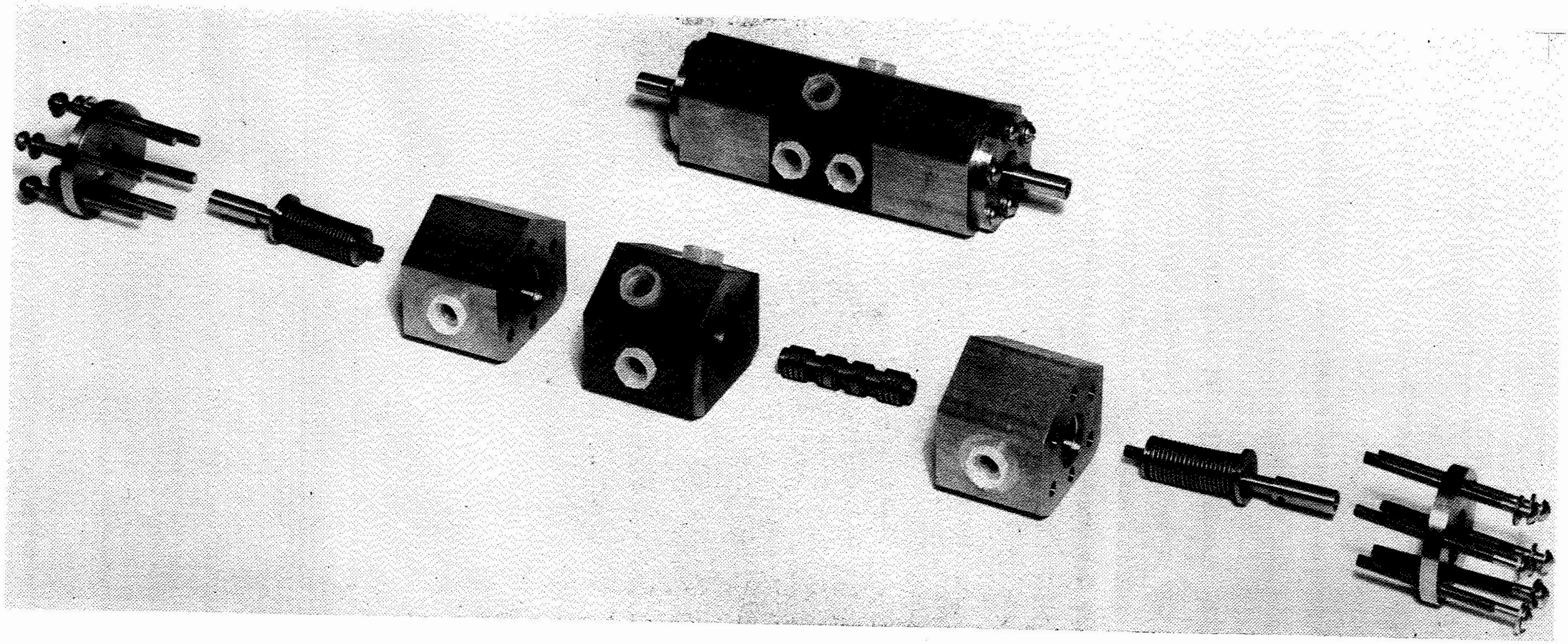

Figure 29. Exploded View of Spool Valve Assembly

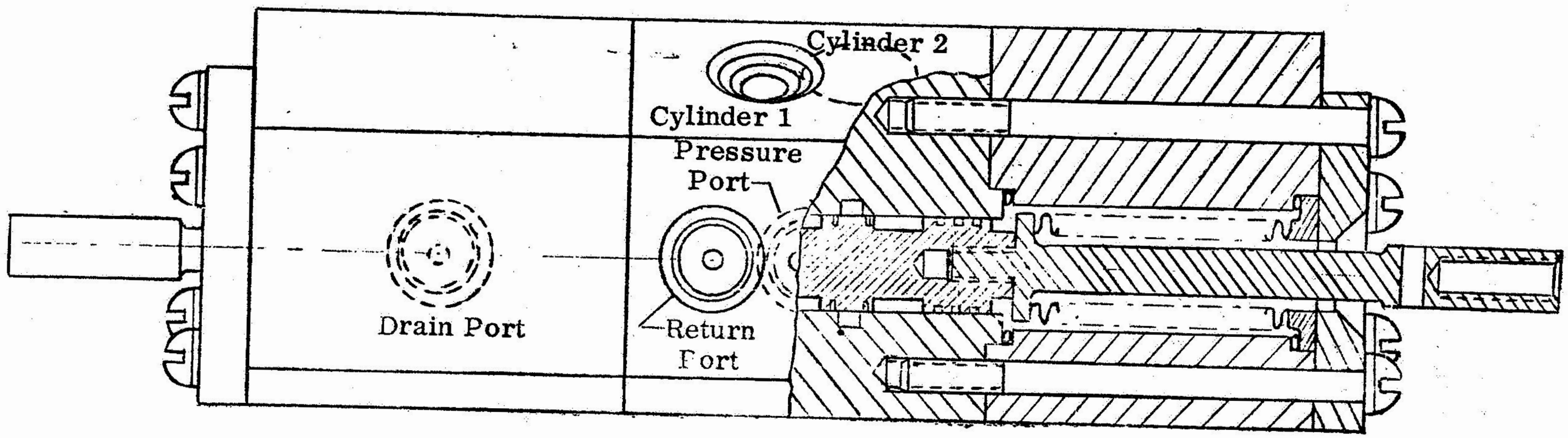

Figure 30. Cross Section of Spool Valve Assembly

The hot spot simulator is located in parallel to the return side of the system and upstream of the cooler. A small portion of the return fluid will be exposed to a maximum temperature of 600°F by a clam shell heater. The skin of the tube in the hot zone is protected by asbestos insulation. Flow through the hot spot simulator will be approximately one-eighth of a gallon per minute.

The sludging effect of the fluid will be monitored by the time required to cause a pressure drop of 500 psi across the pressure line filter using filter elements of 5-, 10-, 17-, and 40-micron nominal sizes. The filter elements are made of stainless steel wire braid and are designed for flows up to 10 gpm.

B. PROGRESS ON 3000-HOUR TEST

Fluids PR-143AB and MLO 60-294 have been subjected to total pumping times of 262 and 136 hours, respectively.

FUTURE WORK

The schedule for the next six-month period of the program is shown in Figure 31.

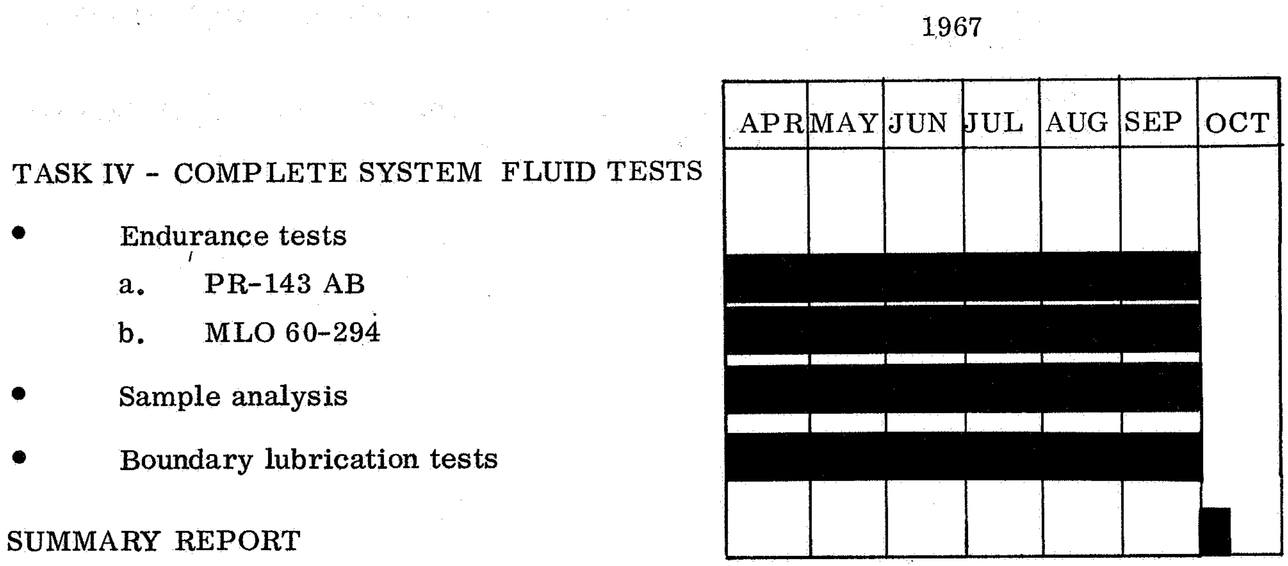

Figure 31. Schedule for the Next Six Months

REFERENCES

1. "A Hi-Mach Turbojet Hydraulic System," D. E. Uehling, ASME Paper 64-WA/LUB-16, November 29-December 4, 1964.

2. "Evaluation of Hydraulic Fluids For Use In Advanced Supersonic Aircraft," NASA CR-54492, October 14, 1965.

3. "Evaluation of Hydraulic Fluids For Use In Advanced Supersonic Aircraft," FHR 2701-2, April 14, 1966.

4. "Part I, Research on High Temperature Hydraulic Fluids for Supersonic Transport Aircraft," RTD-TDR-63-4078, December 1963.

5. "High Temperature Hydraulic Fluids for Supersonic Aircraft," ML-TDR-64-323, December 1964.

6. Correspondence from R. H. Kliemann of Mueller Brass Co. to F. Damasco, Republic, dated June 28, 1965.

APPENDIX

EXHIBIT "A"

SCOPE OF WORK

The Contractor shall furnish the necessary personnel, facilities, services and materials and do all things necessary for, or incident to, the work described below:

The work to be performed shall consist of the evaluation of a number of hydraulic fluids under operating conditions appropriate for use in advanced supersonic aircraft, with a target of 3000 hours of maintenance free high temperature operation.

The work shall include the following Tasks:

TASK I - Determination of Physical and Chemical Properties of Selected Fluids

A. The five fluids listed below, one of which shall be the reference fluid, shall be used by the Contractor:

1. Reference fluid - chlorinated phenyl methyl silicone, General Electric Co., F-50

2. Super refined mineral oil - MLO-60-294

3. Monsanto Co. - modified polyphenyl ether - MCS 293

4. Monsanto Co. - halogenated polyaryl fluid - MCS 310

5. Fluorocarbon polymer - DuPont fluid, PR 143-AB

B. Laboratory evaluation of the five degassed fluids shall be made to obtain data on the following properties:

1. Thermal stability

a. Differential thermal analysis shall be obtained.

b. Thermal stability shall be determined in the Contractor's thermal stability test equipment as follows:

(1) A 30 ml sample of fluid shall be sealed in a stainless steel tube in a nitrogen atmosphere and heated to $600^{\circ}F$ for ten (10) hours. The fluid shall then be cooled; neutralization number, viscosity and appearance shall then be recorded. This test shall be repeated

with fresh fluid at 50°F increments until an appreciable change in properties has been determined by the Contractor to have occurred.

2. Fire resistance

   a. Hot manifold and spray ignition tests shall be made as follows:

      (1) In the hot manifold tests, the test fluid shall be dropped on a pipe heated to 1200°F to determine if ignition occurs.

      (2) In the spray ignition test, fluid shall be sprayed from an orifice with a flaming torch applied to the spray at varying distances from the orifice to determine if ignition occurs.

3. Bulk modulus

   a. Bulk modulus shall be determined on fluids up to and including 600°F.

4. Kinematic viscosity

   a. Shall be determined at -40°, -20°, 0°, 100°, 210°, 400°, 500° and 600°F.

   b. Kinematic viscosity at temperatures up to 400°F shall be determined per ASTM D-445.

   c. Viscosities at temperatures up to 600°F shall be determined in a constant-boiling liquid bath.

5. Acid number

   a. Acid number shall be determined per ASTM D-664.

6. Autogenous ignition temperature

   a. Autogenous ignition temperature shall be determined per ASTM D-286.

7. Flash point

   a. Flash point shall be determined per ASTM D-92.

8. Fire point

   a. Fire point shall be determined per ASTM D-92.

9. Pour point

   a. The pour point shall be determined per ASTM D-97.

10. Density

    a. Density shall be determined in the range of 0° to 600°F.

    b. Density shall be determined by means of a modified version of ASTM D-941, to be recommended by the Contractor and approved by the NASA Project Manager.

11. Coefficient of expansion

    a. This property shall be determined in the range of 0° to 600°F.

    b. Coefficient of expansion shall be determined by means of a modified version of ASTM D-941, to be recommended by the Contractor and approved by the NASA Project Manager.

12. Specific heat

    a. Specific heat shall be determined in the range of 0° to 600°F.

    b. Refer to paragraph "C.", below.

13. Thermal conductivity

    a. This property shall be determined in the range of 0° to 600°F.

    b. Refer to paragraph "C.", below.

14. Vapor pressure

    a. Vapor pressure shall be determined in the range of 0° to 600°F.

    b. This property shall be determined from the differential thermal analysis test. Refer to paragraph "B.1.", above.

15. Nitrogen solubility

    a. This property shall be determined by means of gas chromatography.

16. Compatibility

    a. Compatibility shall be determined with system materials, seal materials and engine oils.

C. Fluid manufacturers' data may be used with specific approval of the NASA Project Manager. Where specific methods of obtaining fluid properties have not been defined, those in use at Pennsylvania State University Petroleum Refining Laboratory under Air Force Contract AF33(616) 7590 shall be acceptable.

D. All ASTM specifications referred to herein are incorporated herein by reference and hereby made a part hereof.

TASK II - Determination of Lubricating Characteristics

A. The boundary lubricating capabilities of the five fluids tested in TASK I shall be measured using four material candidates for the sliders, selected from materials appropriate for a pump and other hydraulic system components for 600°F operation. The choice of material-fluid combinations shall be subject to the approval of the NASA Project Manager. Wear and friction data (including dynamic friction coefficient and volumetric wear data) of the selected twenty material-fluid combinations shall be evaluated at 400°, 500° and 600°F over the surface speeds of 1000, 2000 and 3000 fpm and maximum stress levels encountered in hydraulic systems. Atmospheric controls shall be used to assure inerting. Nitrogen gas (99.99 per cent by volume N_2) containing not more than 50 ppm oxygen and 5 ppm hydrocarbon (as methane) and having a dew point of -90°F or lower shall be used as the cover gas. Prior to testing, the fluids shall be degassed by subjecting them to a pressure of 10^{-3} mm of mercury and temperature between 200° and 240°F for seventy-two (72) hours, or as otherwise approved by the NASA Project Manager.

B. The boundary lubricating capabilities of two (2) fluids selected by the NASA Project Manager, from the five fluids tested in TASK I, shall be evaluated with their optimum bearing materials, using a cover gas having 100 ppm and 1000 ppm oxygen content at 600°F and at surface speeds of 1000, 2000 and 3000 fpm.

C. The surface appearance, as well as the friction and wear data, shall be documented. Specimens shall not be altered after test without prior examination by and/or approval of the NASA Project Manager.

TASK III - Simple Pump Loop Tests

A. The five fluids tested in TASK I shall be run in a simple pump loop. A positive displacement pump which provides an outlet pressure of at least 3000 psi with a reservoir pressure of 50 psi shall be used. The system capacity shall be no more than five gallons, and the system shall not contain air. The test fluids shall be degassed and evacuated to 10^{-3} mm of mercury prior to each test. Nitrogen having the characteristics stated in TASK II shall be used as a cover gas. The system shall provide for flow control and flow and temperature measurement. A heat exchanger shall be provided between a flow restrictor (orifice) and the reservoir to maintain desired reservoir temperatures. Flows in the range 0.5 to 8.0 gallons per minute shall be achieved and periodic flow cycling shall be included in the test procedure. Each test fluid shall be run 50 hours (or until failure of the pump) at each of the test pump inlet temperatures 400°, 500°, and 600°F, in that order. Intermediate values of temperature and/or shorter running times can be used with the approval of the NASA Project Manager. Seals and other system materials shall be optimized for the fluids selected and shall be subject to the approval of the NASA Project Manager.

B. Fluid samples shall be taken for analysis at 5, 10, 20, 30, and 50 hours, as a minimum, for each test of TASK III, subparagraph A. Minimum data to be obtained for each sample shall include kinematic viscosity at 100° and 210°F and the acid number. The pump shall be disassembled at the end of each temperature level of operation and shall be examined for wear, surface failure and corrosion. Operation at the subsequent temperature level shall be without change to the pump and without the addition of new fluid unless specifically approved by the NASA Project Manager. Evidences of wear and deposits in pumps shall be documented photographically at the end of each temperature level of operation. Quantitative wear data shall be obtained. All deposit types found in the system shall be chemically analyzed. Efforts shall be made to establish mechanisms of fluid degradation for test fluids using conductivity measurements, infrared spectrography techniques and other common laboratory methods.

TASK IV - Complete System Fluid Tests

A. Two fluids from among the five fluids tested in TASK I shall be selected by the Contractor with the approval of the NASA Project Manager for evaluation in a complete test system. The test system shall contain servo valves, actuators, loading devices and any other general types of hydraulic equipment that are required for the operation of a complete hydraulic system. Four stainless steel filters with different pore diameters (5, 10, 15, and 20 microns) shall be installed in parallel in the system. Each filter shall be capable of handling the entire flow of the system. Controls shall provide for changing the flow from one size filter to the next larger size filter when the pressure drop across the working filter exceeds a value to be determined by the Contractor with the approval of the NASA Project Manager. The system shall be free of air and the test fluids shall be degassed prior to operation. A nitrogen cover gas with the requirements stated in TASK II shall be used. The system shall operate at pressures up to 3000 psi with fluid temperatures at the pump inlet up to 600°F with a hotspot temperature of 650°F. The system fluid capacity shall be approximately four (4) gallons. Separate systems shall be provided for the two test fluids so that concurrent runs can be made. Seals and other system materials shall be optimized for the fluids selected and shall be subject to the approval of the NASA Project Manager.

B. The values of system temperature and pressure to be used for testing each of the fluids shall be selected on the basis of the results of TASK III with the approval of the NASA Project Manager. The system shall be operated for each fluid for a period of 3000 hours (or until the NASA Contracting Officer shall declare the test to be terminated at a time less than 3000 hours). Fluid samples shall be obtained after 50, 150, 500, 1000, 1500, 2000, 2500 and 3000 hours of operation and the kinematic viscosity at 100°F and at 210°F and the acid number shall be determined.

C. The tests described in TASK II shall be carried out for fluid samples from the complete system tests to determine the lubricating characteristics of the test fluids after 500, 1000, 2000 and 3000 hours of operation. The material from which the primary sliders are made shall be the same as for a given fluid for all tests made under TASK II.

D. The force necessary to actuate a spool valve operating in the system shall be measured continuously during the test. Every component used in the system, including all lubrication surfaces and seals, shall be examined for evidence of wear at the conclusion of the test.